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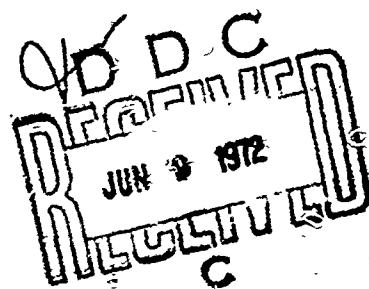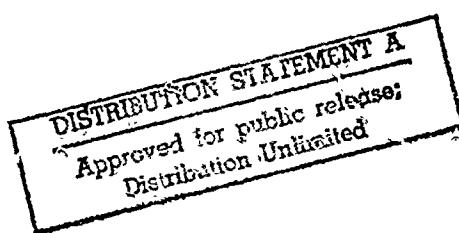
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INVESTIGATION OF SORBENTS FOR REMOVING OIL SPILLS FROM WATERS

Paul Schatzberg
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November 1971

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11 ABSTRACT

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Of all the materials evaluated the polymeric foam and the polymeric hydrocarbon products showed the best overall properties for removing oil spilled on water. Of these two groups, the resilient polyurethane foams and the polypropylene fibers were the best materials. The inorganic, the natural organic, and the miscellaneous products showed a relatively low capacity for oil and a relatively poor buoyancy retention.

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## INVESTIGATION OF SORBENTS FOR REMOVING OIL SPILLS FROM WATERS

By
Paul Schatzberg

### INTRODUCTION

In recognition of the potential application of sorbents for removing spilled oil from water, a large variety of materials is now commercially available for this purpose. Others are being made available after some product development. These materials have considerable variation in composition, structure, and sorptive capacity.

It was the objective of this investigation to find and identify the most effective sorbent materials for removing oil from water. A parallel objective was to develop standardized laboratory procedures for measuring the effectiveness of sorbent materials.

### MECHANISM OF THE SORPTION PROCESS

Close examination of the process by which oil that has spread on water is absorbed by a solid requires consideration of the following factors:

- Cohesive energy of the oil.

- Adhesive energy of the oil on the solid.

- Wetting of the solid by the oil.

- Spreading of the oil on the solid.

- Surface tensions (surface free energy) of the solid and the oil.

- Capillary action.

- Viscosity of the oil.

- Temperature of the environment.

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When sorbent materials are distributed during an oil spill, they can initially contact oil and then water or the converse; in either case, some competition for the solid surface between the two liquids can be expected. For maximum effectiveness, a sorbent material should be hydrophobic and oleophilic. That is, the solid should not be wet by water, but should be wet by oil.

The phenomena of wetting and spreading of liquids on solids has been extensively investigated by Zisman and others.[1] The contact angle $\theta$ (Figure 1) that a drop of liquid makes on a plane solid surface is related to three surface tensions in equation (1), proposed by Young.[2]

$$\gamma_{SV} - \gamma_{SL} = \gamma_{LV} \cos \theta \qquad \ldots\ldots(1)$$

where

$\gamma_{SV}$ is the surface tension at the solid-vapor interface,

$\gamma_{SL}$ is the surface tension at the solid-liquid interface;

and

$\gamma_{LV}$ is the surface tension at the liquid-vapor interface.
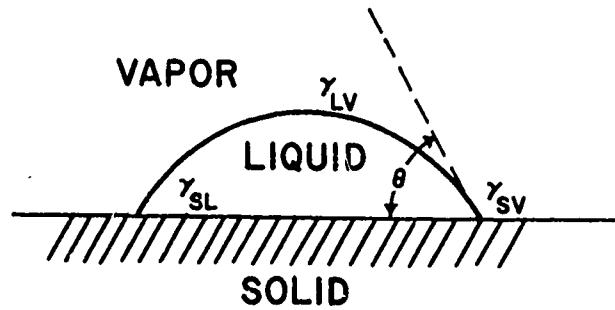


Figure 1
Contact Angle of a Drop

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[1]Superscripts refer to similarly numbered entries in the Technical References at the end of the text.

Thus, a liquid is nonspreading when $\theta \neq 0°$; and when the liquid wets the solid completely, spreading over the surface, $\theta = 0°$. Another equation, introduced by Dupré,[3] relates the reversible work of adhesion of a solid and liquid, $W_A$, to the three surface tensions

$$W_A = \gamma_{SV} + \gamma_{LV} - \gamma_{SL}. \qquad \ldots\ldots(2)$$

Combining equations (1) and (2) leads to equation (3)

$$W_A = \gamma_{LV}(\cos\theta + 1). \qquad \ldots\ldots(3)$$

The spreading coefficient S has been defined[4] as

$$S = \gamma_{SV} - \gamma_{SL} - \gamma_{LV}. \qquad \ldots\ldots(4)$$

Combining equations (1) and (4) leads to equation (5)

$$S = \gamma_{LV}(\cos\theta - 1). \qquad \ldots\ldots(5)$$

Equations (3) and (5) describe adhesion and spreading without the terms $\gamma_{SV}$ and $\gamma_{SL}$ which are difficult to measure. It has also been shown[5] that

$$S = W_A - W_C \qquad \ldots\ldots(6)$$

where $W_C$ is the reversible work of cohesion of the liquid. Relating equations (3) and (6) leads to

$$S = \gamma_{LV}(\cos\theta + 1) - W_C. \qquad \ldots\ldots(7)$$

For spreading $S > 0$ and for nonspreading $S \leq 0$.

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A rectilinear relation has been established[1] between the cosine of the contact angle θ and the surface tension $\gamma_{LV}$ for each homologous series of organic liquids such as the normal hydrocarbons. The liquid surface tension at which cosine θ = 1 for a solid is defined as $\gamma_C$, the critical surface tension of that solid. Liquids with surface tensions less than the $\gamma_C$ of a solid will spread on that solid. For example, a hydrocarbon liquid such as hexamethyltetracosane (squalane, $C_{30}H_{62}$) with a surface tension of 28 dynes per centimeter (/cm) would spread on polyethylene ($\gamma_C$ = 31 dynes/cm), but not on polytetrafluorethylene (Teflon, $\gamma_C$ = 18 dynes/cm). Water with a surface tension of 72 dynes/cm would not spread on either solid. This indicates that forms of polyethylene should be good sorbents for oil. Many natural and synthetic organic solids have values of $\gamma_C$ that are larger than the surface tensions of petroleum products but smaller than the surface tension of water so that wetting and spreading of oil on these solids preferentially to water can be expected. Inorganic solids that do not have the required value of $\gamma_C$ can be modified by various surface treatments to produce the desired condition.

With some solids, wetting does not only involve the contact angle the liquid makes on its surface. If the solid consists of fine capillaries or pores, the sorption of the liquid would also involve capillary rise, where the driving force is that of the pressure difference across the curved surface of the liquid meniscus.

The rate of entry v of a liquid into a capillary has been described[8] by equation (8)

$$v = (r \; \gamma_{LV})/(4 \; d \; \eta) \cos \theta \qquad \ldots\ldots(8)$$

where r is the radius of curvature of the capillary; $\gamma_{LV}$ and η are the surface tension and viscosity of the liquid, respectively; d is the depth of penetration and θ the angle of contact between the liquid and the capillary wall. If θ = 0°, for the oil/sorbent contact angle, cosine θ becomes unity and equation (8) reduces to

$$v = (r \; \gamma_{LV})/(4 \; d \; \eta). \qquad \ldots\ldots(9)$$

Equation (9) demonstrates that the rate of penetration of an oil into a capillary is inversely proportional to the oil's viscosity and directly proportional to the capillary radius. Spilled petroleum products have a viscosity range of three orders of magnitude. Consequently, depending on the capillary diameter of sorbent materials, oil penetration rates could be fast (seconds) as in a jet fuel or slow (hours) as in a Bunker C oil. If $\theta = 90°$ for water/sorbent contact angles, cosine $\theta$ becomes 0 and the penetration rate would be 0 for water entering a capillary.

The foregoing has been a theoretical description of the basic phenomena that would be operating in the process of sorption of oil by a sorbent in the presence of water. In the real situation, a number of other factors must be recognized. It has been shown[7] that a hydrocarbon mixture spreads on a solid by the advance of a primary film less than 1000Å thick usually followed by a thicker secondary film. The movement of the secondary film results from a surface tension gradient across the transition zone between the primary and secondary films. This gradient is produced by the unequal depletion by evaporation of the more volatile constituents having a lower surface tension. Thus, volatile constituents in spilled oil would serve to enhance spreading of the oil through the sorbent. However, if a spill remains uncollected, it loses the volatile constituents which have the greatest effect on spreading. In addition, evaporative loss of the oil constituents increases the viscosity of the residue which will decrease the spreading rate. When the spilled oil ceases to flow due to low ambient temperatures, its viscosity becomes so high that no spreading occurs. Although the surface tension of water is high, it can be significantly reduced by the presence of surface active materials. Thus, the presence of detergents, as contaminants in water along the coast or due to attempts to disperse spilled oil, can seriously interfere with the effective use of sorbents since the detergents will permit water to wet and spread on the sorbents and thereby compete with the oil. Surface-active components of spilled oil can also affect the wetting characteristics of water. Similarly, the use of surface-active agents to retard spreading of oil on water could interfere with the subsequent use of sorbent materials.

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It is shown by equation (7) that the cohesive energy of a liquid, $W_c$, opposes spreading on a solid. In some cases, however, cohesive energy can operate favorably. If the sorbent consists of loose powder or loose fibers, the cohesive energy of the oil between the particles can serve to produce a congealed mass.

In addition to the wetting, spreading, and capillary phenomena involved in the sorption process, a high surface-to-solid volume ratio is a basic necessity. Once a material has the desired wetting characteristics, its sorption capacity is proportional to the material's exposed surface area.

## PROPERTIES NEEDED FOR EFFECTIVE UTILIZATION OF SORBENTS

From the foregoing considerations as well as practical aspects, sorbents for removing oil from water should have the following properties:

• Buoyancy retention in water by themselves or in combination with oil.

• Solid surface tension (critical surface tension) which will permit wetting and spreading of petroleum products, not water. That is, the material must be oleophilic and hydrophobic.

• Open-end porous structure with pores large enough to allow easy access and penetration of oil, but small enough to retain oil within its matrix.

• Ability to retard spreading of the oil.

• Rapid oil sorption to minimize contact time and need for mixing.

• High surface-to-solid volume ratio.

• High capacity for oil.

• Easy separation of the oil from the sorbent to permit reuse and to facilitate ultimate disposal.

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Some of these properties have overlapping aspects. While all are desirable in a sorbent, ultimate selection of the best materials will involve a compromise between the most essential properties and other factors such as material availability, use experience in a spill, available equipment for distribution and harvesting, spill location, etc.

Effective use of sorbents involves transportation to the scene of the spill, dispersal onto the spill, recovery, and disposal. For an oil spill of significant size this entails large amounts of materials. It is apparent, therefore, that a key property of a sorbent is to permit easy on-site separation of the oil and reuse (recycling) of the sorbent.

## SORBENT EVALUATION METHODOLOGY

While some data on sorbent materials have been published,[8,9] a systematic laboratory evaluation of many sorbents being considered for or already in use has not been reported. Such information is needed to assist in the selection of sorbents for a variety of uses in cleaning up oil spills and in establishing design criteria for sorbent dispersal and recovery systems currently being developed. A recent investigation[10] on test procedures for evaluating oil spill treating agents found no identifiable set of testing methods available for sorbents.

Since a large number of potential sorbent materials needed to be evaluated, emphasis was placed on developing simple laboratory procedures designed to identify the most promising materials. Of primary interest are the buoyancy, oil sorption capacity, water sorption capacity, oil/sorbent coherence, and oil retention of sorbents. It was recognized that many factors involved in the ultimate application of sorbents were not relevant in method development since different sorbent materials could have specific applications difficult to anticipate. Thus, emphasis was placed on screening materials to identify those having the best basic properties, such as buoyancy retention and oil sorption capacity. After identifying the most promising sorbents, additional laboratory tests were applied to determine reusability characteristics, mechanical strength, sorption rates, drainage rates, and the influence of temperature and water quality on oil sorption capacity.

## BUOYANCY

In order to function as a means for separating spilled oil from the water environment, sorbents must remain afloat for several hours whether contacted by oil or water. If sorbents sink before or after contact with oil, more pollutants are added to the environment. A number of sorbents, while floating initially, have been found to sink after some time. While it is preferable to apply a sorbent directly to the oil slick, to take advantage of the buoyancy the oil would thereby impart to the sorbent, it is not always feasible to do so. In fact, the oil/sorbent mixture should be more buoyant than the oil itself to facilitate recovery. In some cases it may be desirable to apply sorbents in advance of an onshore moving slick. Further, it may be necessary to suspend operation in bad weather, returning later to recover oil-soaked sorbents. Therefore, it was necessary to determine which sorbents demonstrated the best buoyancy under agitation, with and without prior oil contact. This is done by vigorously agitating a weighed quantity of sorbent with synthetic sea water for 6 hours (half a tidal cycle). At the end of that time the percentage of sorbent remaining afloat is determined by visual estimate. This test is repeated with oil-soaked sorbent.

## OIL SORPTION CAPACITY

Under field conditions, the amount of oil absorbed is not only a function of the sorbent's properties, but also a function of the available mixing energy from waves and wind, oil film thickness, rature of the petroleum product, and water quality. Therefore, to evaluate a large number of sorbents in terms of their relative oil sorption capacities, idealized conditions must be created. Consequently, a weighed quantity of the sample is soaked in oil for 15 minutes with frequent agitation to bring about saturation. This determines each sorbent's maximum oil sorption capacity for the particular petroleum product used. In addition, the oil sorption capacity is determined after prior contact of the sorbent with sea water.

## WATER SORPTION CAPACITY

This property is a measure of the sorbent's hydrophobic nature; that is, how well it can resist wetting by

water. Thus, the most hydrophobic materials will absorb
the smallest amount of water. If potential oil sorbents
absorb significant amounts of water, their capacity for oil
sorption will be reduced. Water sorption capacity is deter-
mined by vigorously agitating a weighed quanity of sorbent
with synthetic sea water for 30 minutes, for 6 hours, and
determining the amount of water absorbed in each case. The
short time period provides information quickly, while the
longer period evaluates the effect of half a tidal cycle.

OIL/SORBENT COHERENCE

     This property is of interest since it indicates the
ease or difficulty to be encountered in recovering the oil/
sorbent mixture from the water. The coherence appears to
be a function of the sorbent material and the petroleun
product, and may in many cases be primarily a function of
the viscosity of the petroleum product. Thus, a viscous
oil such as Bunker C oil would form a very coherent mass
with the sorbent, which would be relatively easy to remove
from the water intact, while a No. 2 fuel oil would result
in a loose mass, permitting some of the oil to remain on the
water after the sorbent is removed. The oil/sorbent coher-
ence is determined qualitatively by observation after shaking
the oil-soaked sorbent with sea water for 6 hours. Coher-
ence is described in two ways: first, whether the oil-soaked
sorbent floats on water in clumps or whether a viscous but
fluid mass is formed; and second, whether the oil/sorbent
mixture is retained on or passes through a wire mesh screen
having 1/16-inch openings. Figure 2a-d is a photograph which
illustrates oil/sorbent coherence variation. The sorbent is
the same in all four bottles and consists of a polyether-type
polyurethane foam in 1/2-inch cubes. In each case the sorbent
was saturated with a different oil and shaken for 6 hours
with sea water. The oils used in Figures 2a and 2b were a
heavy crude and Bunker C, respectively. The oils used in
Figures 2c and 2d were a No. 2 fuel and a light crude,
respectively. The difference in the final product is illus-
trated by the photographs.

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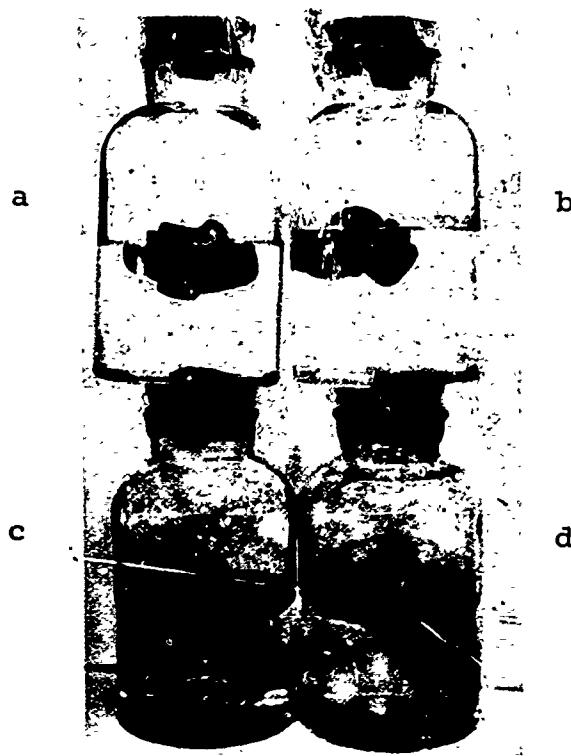
Figure 2a-d
Oil/Sorbent Coherence

## OIL RETENTION

Oil retention is related to oil/sorbent coherence, but is measured quantitatively. After the oil-soaked sorbent is shaken with sea water for 6 hours, it is separated from the sea water and the amount of oil retained by the sorbent determined.

## REUSABILITY

Unless sorbent materials can be reused many times during an oil-spill cleanup operation, large amounts of sorbents will have to be stock-piled, transported, and disposed after being soaked with oil. Easy separation of oil from the sorbent along with continued high capacity for oil is desired. The most economical way to remove oil from sorbents appears to be by squeezing. To evaluate this property selected sorbents were soaked in oil and then

squeezed through rollers to remove the oil. This process was
repeated a number of times and for each cycle the quantity
of oil sorbed was determined.

The foregoing properties are considered the most signif-
icant that can be determined under laboratory conditions for
oil sorbent materials. Procedures have been developed by
which these properties can be determined. Details of these
procedures are described in Appendix A.

PETROLEUM PRODUCTS

Four petroleum products were used in the sorbent eval-
uation procedures: a No. 2 fuel oil, a light crude oil
(South Louisiana), a heavy crude oil (Venezuela), and a
Bunker C oil. These oils were obtained from the Edison
Water Quality Laboratory, Environmental Protection Agency.
Table 1 lists these products along with some of their
pertinent physical properties.

TABLE 1
PROPERTIES OF PETROLEUM PRODUCTS

| Oil Type | No. 2 Fuel | Light Crude (South Louisiana) | Heavy Crude (Venezuela) | Bunker C |
|---|---|---|---|---|
| Specific Gravity, 77° F | 0.856 | 0.854 | 0.977 | 0.942 |
| API°, 77° F | 33.8 | 34.2 | 13.3 | 18.9 |
| Kinematic Viscosity, Cs, 77° F | 3.1 | 7.8 | 2600 | 2800 |
| Pour Point, ° F | -10 | 10 | 15 | 65 |
| Surface Tension, 77° F, dynes/cm | 37.1 | 34.2 | 38.6 | 39.9 |
| Interfacial Tension with synthetic sea-water, 77° F, dynes/cm | 36 | 24.9 | 37.8 | 46.2 |
| Emulsification Characteristics with synthetic seawater, 77° F, time for separation | 3 min. | 65 min. | 2 hr. | none after 2 weeks |

## PRECISION OF METHODS

All measurements of mass were made with a top-loading analytical balance having a precision of ±0.01 gram. Since weighing constitutes the most precise step in the procedures (Appendix A), it contributes only a negligible error. Experimental errors that contribute to the reduction of precision are explained as follows:

- **Oil Drainage.** The 15-minute oil drainage period was considered adequate since longer periods did not result in sufficient weight reduction to warrant additional waiting time. However, some error in sorption capacity may be introduced in this step particularly for the viscous oils.

- **Sorbent Nonuniformity.** Some sorbent materials lack uniformity in particle size and composition which can contribute to variations in oil sorption capacity.

- **Transfer Operations.** Some material is lost when the oil/sorbent mixture is transferred from the screen, sieve, or bottle prior to weighing. For the case of those sorbents consisting of fine powders, some material is lost despite the use of a fine mesh sieve.

Repeatability of the measurement of oil sorption capacity was assured by performing a number of duplicate and triplicate determinations on 20 sorbent materials using four test oils. Test results on these 20 sorbents were presented in a technical paper.[11] For each set of replicates the deviation from the average was determined and expressed as percent precision. The overall average was determined and expressed as percent precision. The overall average precision was determined from 80 sets of replicates shown in Appendix B. This analysis shows that the overall average precision is ±5%. This is considered good for the evaluation of sorbents since it adequately distinguishes effectiveness between different materials.

Many additional measurements of oil and water sorption capacity have shown that this precision is maintained. Further evidence on the validity of the evaluation test methods is presented in the Results section, which show good agreement with other laboratories.

## SORBENTS

Forty-nine sorbent materials were evaluated. These were separated into the following categories: Inorganic, natural organic (vegetable origin), polymeric hydrocarbon, polymeric foam, and miscellaneous products. Tables 2-6 list each of these materials in their respective categories, along with descriptive information. By consulting Appendix C, a code designation next to each item permits identification of the source. Appendix D consists of photographs (to scale) of each material.

### TABLE 2
### INORGANIC PRODUCTS

| Code | |
|------|---|
| I-1 | Asbestos (Chrysotile) - White, dusty powder, treated, bulk density 20 lb/ft$^3$ |
| I-2 | Carbon Composite - Black, extruded strings, 1/16-inch diameter, 1-2 inches long, 98% carbon, flexible, fragile, bulk density 11 lb/ft$^3$ |
| I-3 | Fly Ash Component - Gritty gray powder, power-plant by-product, hollow glass spheres |
| I-4 | Perlite- White powder, expanded, fines to 1/8-inch diameter particles, treated to make hydrophobic, bulk density 6 lb/ft$^3$ |
| I-5 | Talc - Very fine, white, dusty powder, zinc stearate coated, bulk density 4 lb/ft$^3$ |
| I-6 | Vermiculite A - Brown particles, 1/16-inch cubes, expanded, treated, bulk density 7 lb/ft$^3$ |
| I-7 | Vermiculite B - Yellow particles, 1/8 to 1/4-inch cubes, expanded, treated, bulk density 7 lb/ft$^3$ |
| I-8 | Volcanic Ash - Very fine, dry, gray, free-flowing powder, expanded, bulk density 7 lb/ft$^3$ |

## TABLE 3
## NATURAL ORGANIC PRODUCTS (VEGETABLE ORIGIN)

| Code | |
|------|---|
| N-1 | Corn Cob (ground) - Reddish-brown to yellowish-white flakes and particles from fines to 1/8-inch diameter, bulk density 12 $lb/ft^3$ |
| N-2 | Cellulose, Bleached - White, fluffy, fibrous material, bulk density 14 $lb/ft^3$ |
| N-3 | Cellulose, Wood Fibers - Fine, fluffy, yellow fibers, some lumps, bulk density 14 $lb/ft^3$ |
| N-4 | Cellulose, Wood Fiber Mat - Off-white, 1/2-inch thick, soft, flexible, density $0.045$ $lb/ft^2$, polypropylene net backing |
| N-5 | Fiberboard, Recycled - Yellow-tan, fluffy fibers, bulk density 14 $lb/ft^3$ |
| N-6 | Hay - Dried grass, stalks, and blades |
| N-7 | Peanut Hulls, Ground - Tan flakes, fines to 1/16-inch diameter |
| N-8 | Pinebark, Ground - Dark-brown, moist, fine particles |
| N-9 | Mulch - Pale, gray-green, dusty fibers |
| N-10 | Paper, Pulverized - Finely ground newsprint, gray fibrous mass |
| N-11 | Redwood, Shredded - Reddish-brown, fluffy fibers |
| N-12 | Sawdust - Small chips, flakes, granules, light-brown |
| N-13 | Straw, Wheat - Coarse, yellow stalks, and blades |
| N-14 | Straw, Wheat, Treated - Coarse, yellow stalks, and blades with a spotty coating of white grains |
| N-15 | Wheat Middlings - Fine, tan fibers |
| N-16 | Wood Chips A - Brown particles of wood |
| N-17 | Wood Chips B - Tan squares of wood, 1/32-inch-thick and $1/8-inch^2$ |

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## TABLE 4
## POLYMERIC FOAM PRODUCTS

| Code | Polyurethane (Open Cell) |
|------|--------------------------|
| F-1 | Polyether, Shredded - (A) - Reduced to shredded form with a blending machine from a rigid, fragile foam having a bulk density of 0.6 lb/ft$^3$ |
| F-2 | Polyester, Reticulated - (B) - Uniform, open cell, spongy structure, 80 pores per linear inch, 97% free volume, resilient, bulk density 3 lb/ft$^3$ |
| F-3 | Polyether, 1/2-Inch Cubes - (C) - Pale yellow color, bulk density 0.6 lb/ft$^3$, resilient |
| F-4 | Urea Formaldehyde - Foam, white, partially open cell, very fine pores, brittle, bulk density 1 lb/ft$^3$ |

## TABLE 5
## POLYMERIC HYDROCARBON PRODUCTS

| Code | Polyethylene |
|------|--------------|
| H-1 | Fiber, Continuous - linear polyethylene, white continuous filament |
| H-2 | Fiber, Sheet, Matted - White, nonwoven, soft, nonoriented fibers, 1/16-inch-thick |
| H-3 | Fiber, Loose - Loose agglomerates of fluffy, white fibers |
| H-4 | Powder, Fine - Fine, white powder, free flowing, 5 lb/ft$^3$ |
| H-5 | Granules, Waste - Coarse, chopped, or shredded granules, gray-green |
| | **Polypropylene** |
| H-6 | Fiber, Bulk A - Densely matted agglomerate of very fine white fibers |
| H-7 | Fiber, Bulk B - Random agglomerate of fine fibers, neutral color |
| H-8 | Fiber, Strands - Clear white, shiny fibers, rectangular cross-section |
| H-9 | Fiber, Sheet - Spun-bonded, 1/16 to 1/8-inch-thick, bulk density 1 lb/ft$^3$ |
| H-10 | Powder - Fine, white, free-flowing, dustless powder, bulk density 45 lb/ft$^3$ |
| H-11 | Polystyrene Powder - Irregular shape, white particles, free-flowing |

## TABLE 6
## MISCELLANEOUS PRODUCTS

| Code | |
|------|---|
| M-1 | Cellulose Fiber-Perlite Mixture A – Brown, fibrous lumps containing white specks of perlite, bulk density 6 lb/ft$^3$ |
| M-2 | Cellulose Fiber-Perlite Mixture B – Brown, fibrous lumps containing white specks of perlite, bulk density 6 lb/ft$^3$ |
| M-3 | Fibrous Mixture – Brown, fibrous powder containing a few light colored specks, bulk density 6 lb/ft$^3$ |
| M-4 | Polyester Plastic Shavings – Feathery particles, 1/8-inch long, off-white, free-flowing |
| M-5 | PTFE Shavings – Polytetrafluorethylene (PTFE), white opaque machine turnings |
| M-6 | Refuse Compost – Appearance of dark soil with bits of hard particles, such as glass and metal |
| M-7 | Synthetic Fiber Mixture – Dark gray color, consists of nylon, rayon, polyester, and other fibers |
| M-8 | Synthetic Organic Powder – Fine, free-flowing, appearance of fine yellow sand, bulk density 6 lb/ft$^3$ |
| M-9 | Wood-Coal- Polyethylene – Lumps of pulverized coal dust containing wood chips with nonvisible polyethylene binder |

## RESULTS

### BUOYANCY CHARACTERISTICS

Results of buoyancy determinations are summarized in Table 7. This summary consists of averages from the results presented in Tables 1-E to 5-E of Appendix E. Although these results are based on visual observations, they provide sufficient information on the buoyancy characteristics of these materials. Photographs of a number of these sorbents after shaking in sea water for 6 hours are shown in Appendix E.

## TABLE 7
### BUOYANCY CHARACTERISTICS

| Products | Percent Afloat After Shaking in Water for | | Percent Afloat After Shaking Oil-Soaked Sorbent in Water for 6 Hours | | | |
| | 30 Min | 6 Hr | No. 2 Fuel | Light Crude | Heavy Crude | Bunker C |
|---|---|---|---|---|---|---|
| Inorganic | 75 | 60 | 90 | 93 | 96 | 97 |
| Natural Organic | 50 | 30 | 50 | 75 | 100 | 100 |
| Polymeric Hydrocarbon | 100 | 100 | 100 | 100 | 100 | 100 |
| Polymeric Foam | 100 | 95 | 100 | 100 | 100 | 100 |
| Miscellaneous | 90 | 60 | 100 | 95 | 100 | 100 |

Table 7 shows that the inorganic, natural organic, and miscellaneous products have relatively poor buoyancy characteristics. Very good buoyancy is shown by the polymeric hydrocarbon and foam products.

## OIL SORPTION CAPACITY

Maximum oil sorption capacity is expressed in grams of oil per gram of sorbent (g/g). Table 8 is a summation of the results for all sorbents presented as the average capacities of each sorbent category or product type for each of the four test oils. This summation is presented graphically in Figure 3. The highest oil sorption capacity is exhibited by the polymeric foam products. The polymeric hydrocarbon products exhibit average oil sorption capacities that range from one-third to less than half that of the foam products. By comparison, the average oil sorption capacities of the natural organic, inorganic, and miscellaneous products are low. Results for each of the sorbents evaluated are given in Tables 1-F to 5-F of Appendix F.

## TABLE 8
## AVERAGE MAXIMUM OIL SORPTION CAPACITIES, g/g
### (RANGE OF CAPACITIES)

| Test Oils | Bunker C | Heavy Crude | Light Crude | No. 2 Fuel | Average for all oils |
|---|---|---|---|---|---|
| Test Oil Viscosity at 77°F, cs | 2800 | 2600 | 7.8 | 3.1 | |
| Inorganic | 9.4 (2.8-21.6) | 8.0 (2.6-18.1) | 3.4 (1.7-7.2) | 2.9 (1.2-5.0) | 6.2 |
| Natural Organic | 10.7 (1.8-26.3) | 9.4 (1.6-20.3) | 5.8 (0.7-12.7) | 4.8 (0.8-12.7) | 7.8 |
| Polymeric Foam | 62.2 (30.3-72.9) | 55.8 (24.5-74.8) | 51.S (30.6-66.1) | 47.2 (27.5-64.9) | 54.2 |
| Polymeric Hydrocarbon | 28.3 (4.4-66.0) | 25.3 (3.2-64.8) | 17.3 (1.1-45.4) | 14.5 (1.0-40.5) | 21.4 |
| Miscellaneous | 12.0 (1.0-40.3) | 9.6 (1.0-20.8) | 5.7 (0.6-9.8) | 4.5 (0.6-8.7) | 8.0 |
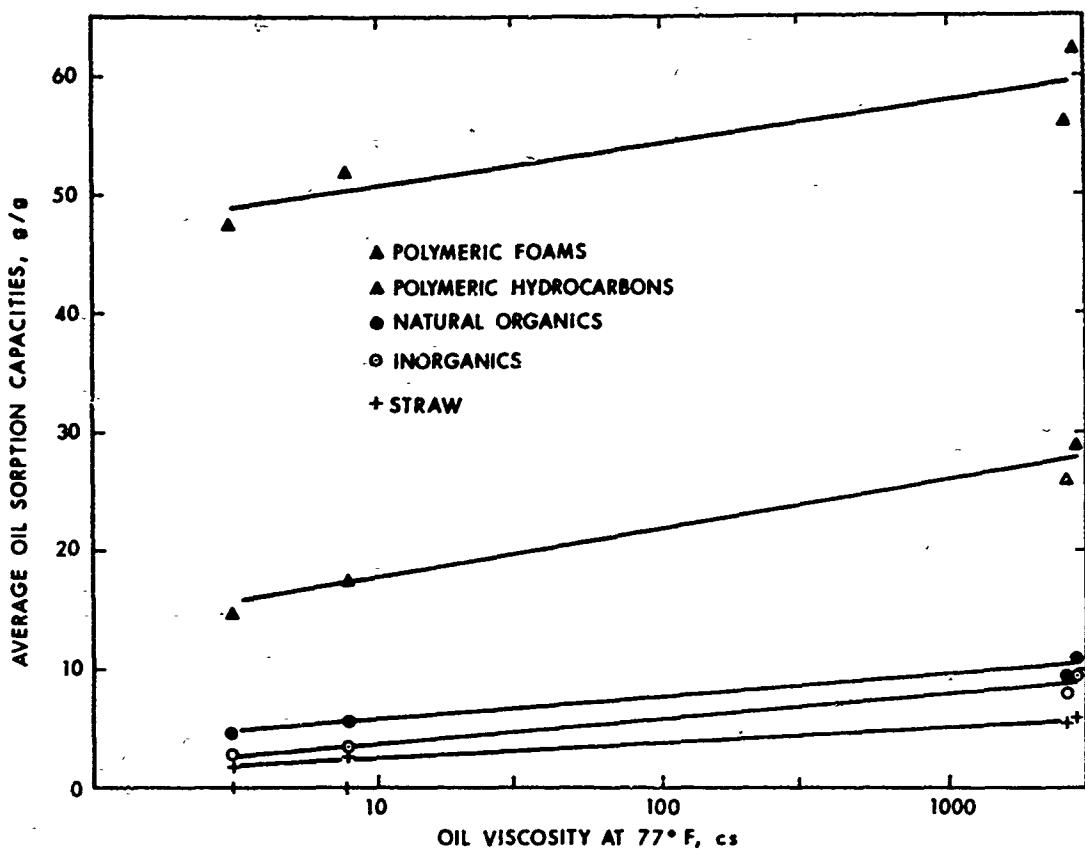
Figure 3
Average Oil Sorption Capacities for Product Type

Results of oil soption capacity measurements were compared with those of two other laboratories. These comparisons were limited to sorbents, test oils, and test methods that were either the same or very similar. Results were taken from a report of the U. S. Naval Civil Engineering Laboratory[12] and of the Shell Pipe Line Corporation.[13] Table 9 presents the comparisons which are remarkably good in most cases, providing additional evidence on the validity of the evaluation test methods.

## TABLE 9
## COMPARISON OF RESULTS WITH OTHER LABORATORIES

### A. Light[1] Oil Sorption Capacity, g/g

| Sorbents | NCEL[2] | Shell[3] | Annapolis Laboratory |
|---|---|---|---|
| Hay | - | 1.1 | 1.2 |
| Sawdust | - | 2.1 | 2.8 |
| Straw | 3.1 | - | 1.8 |
| Wood Chips | - | 0.5 | 1.0 |
| Perlite | 1.8 | 3.7 | 3.0 |
| Polypropylene sheet | 1.3 | - | 1.2 |
| Polystyrene powder | 11.1 | - | 5.8 |
| Polyurethane foam | 21.4 | 27.7 | 27.5 to 64.9 |

### B. Bunker C[4] Oil Sorption Capacity, g/g

| Sorbents | NCEL | Shell | Annapolis Laboratory |
|---|---|---|---|
| Hay | - | 5.1 | 8.8 |
| Sawdust | - | 3.6 | 4.0 |
| Straw | 5.9 | - | 5.8 |
| Wood Chips | - | 1.1 | 2.8 |
| Perlite | 3.7 | 5.3 | 4.6 |
| Polypropylene sheet | 4.2 | - | 4.4 |
| Polystyrene powder | 19.1 | - | 23.4 |
| Polyurethane foam | 38.6 | 51.2 | 30.3 to 72.9 |

[1]Viscosity in cs at 77° F: NCEL-3.8; Shell-3.5;
NAVSHIPRANDCEN Annapolis Laboratory-3.1
[2]NCEL, Port Hueneme, Calif.
[3]Shell Pipe Line Corporation, Research and Development
Laboratory, Houston, Texas.
[4]Viscosity 2800 cs at 77° F.

Oil sorption capacity measurements were also compared
to large scale test results.[9] These results showed oil-to-
sorbent weight ratios for perlite (5), hay (4), urea
formaldehyde foam (26) and a polyurethane foam (46), all of
which are similar to results reported in this investigation.

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Consequently, laboratory results presented in this investigation can be applied to the selection of sorbents for large scale operations.

In addition to separating the sorbents into product categories they were also separated into the following structure types: fibers, granules, powders, and foams. Table 10 gives the average oil sorption capacities for these sorption structure types in an attempt to illustrate the influence of morphology on sorbent effectiveness. The superior oil sorption capacity of the foams is clearly illustrated.

TABLE 10
AVERAGE OIL SORPTION CAPACITIES FOR SORBENT
STRUCTURE TYPES, g/g

| Test Oil | Bunker C | Heavy Crude | Light Crude | No. 2 Fuel | Overall Average |
|---|---|---|---|---|---|
| Test Oil Viscosity at 77° F, cs | 2800 | 2600 | 7.8 | 3.1 | |
| Fibers | 21.6 | 18.3 | 12.4 | 11.7 | 15.9 |
| Granules | 4.6 | 4.5 | 2.8 | 2.3 | 3.5 |
| Powders | 20.6 | 20.9 | 9.2 | 5.7 | 16.2 |
| Foams | 62.2 | 55.8 | 51.8 | 47.2 | 54.2 |

Since all determinations in the laboratory procedures of Appendix A were conducted under ambient temperature conditions (77° F), measurements of oil sorption capacity were made with the same procedure at 40° F to determine the influence of temperature. Table 11 presents the ratios of the oil sorption capacities determined at 40° and 77° F for five different sorbent materials. These ratios showed that higher oil sorption capacities are attained at the lower temperature, although a consistent trend is not indicated. Figure 3 illustrates that higher oil sorption capacities are attained at higher oil viscosities. However, it requires a viscosity increase of _three_ orders of magnitude to double the oil

sorption capacity. A temperature change from 77° to 40° F does not produce such an increase in viscosity, as demonstrated in Table 11. The one order of magnitude increase in viscosity of the heavy crude oil is probably due to the precipitation of wax particles. The Bunker C oil could not be included in these tests since it would be a solid at 40° F.

TABLE 11
INFLUENCE OF TEMPERATURE ON OIL SORPTION CAPACITY

| Test Oils | No. 2 Fuel | Light Crude | Heavy Crude |
|---|---|---|---|
| Viscosity in cs at 40° F | 5.5 | 16.0 | 26,000 |
| Viscosity in cs at 77° F | 3.1 | 7.8 | 2,600 |

Oil Sorption Capacity Ratios, 40° F/77° F

| | No. 2 Fuel | Light Crude | Heavy Crude |
|---|---|---|---|
| Polyurethane foam (A), polyether, shredded | 1.46 | 1.02 | 1.17 |
| Polyurethane foam (B), reticulated, 80 ppi | 1.02 | 1.00 | 1.05 |
| Polyethylene fiber, loose | 1.17 | 1.11 | 1.05 |
| Cellulose, wood fiber | 1.04 | 1.11 | 1.73 |
| Straw, wheat | 1.04 | 1.12 | 1.26 |

ppi = pores per inch

WATER SORPTION CAPACITY

As previously stated, one property of an oil sorbent is to be hydrophobic or reject water; the amount of water that a sorbent retains is therefore inversely proportional to its hydrophobicity. The water sorption capacity, expressed in grams of water per gram of sorbent (g/g), is presented in Tables 1-G to 5-G of Appendix G. A summation of these results is given in Table 12. By far the highest capacity for water is exhibited by the foams, which is an undesirable sorbent property.

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## TABLE 12
## WATER SORPTION CAPACITY

| Products | Water Sorption Capacity, g/g After Shaking for | | | |
|---|---|---|---|---|
| | 30 Minutes | | 6 Hours | |
| | Average | Range | Average | Range |
| Inorganic | 3.3 | (0.4-5.3) | 3.5 | (0.5-5.3) |
| Natural Organic | 6.4 | (0.6-15.2) | 7.4 | (0.7-15.2) |
| Polymeric Foam | 32.1 | (18.1-40.9) | 37.5 | (26.6-48.2) |
| Polymeric Hydrocarbon | 5.8 | (0.5-30.7) | 7.6 | (0.7-28.0) |
| Miscellaneous | 4.2 | (0.5-9.6) | 4.8 | (0.8-9.8) |

Comparison of water sorption capacity results with those of another laboratory are shown in Table 13. As in the comparisons of oil sorption capacities, reasonably good agreement exists.

## TABLE 13
## COMPARISON OF WATER SORPTION CAPACITIES, g/g

| | NCEL | Annapolis Laboratory |
|---|---|---|
| | 20 min agitation at 100 RPM | 30 minute shake at .140 cpm |
| Straw | 6.0 | 2.3 |
| Perlite | 2.6 | 3.8 |
| Polypropylene sheet | 0.8 | 0.6 |
| Polystyrene powder | 15.0 | 14.4 |
| Polyurethane foam | 14.8 | 18.1 to 40.9 |

## OIL/WATER SORPTION CAPACITY RATIO

As stated earlier, a good oil sorbent should be oleo-
philic and hydrophobic; that is, have a high affinity for
oily materials and a low affinity for water. This can be
expressed in terms of the sorbent's oil/water sorption capac-
ity ratio or as the material's oil preference.[12] Table 14
is a summation of these ratios for all sorbents, presented
as the average of each product category for each of the four
test oils. This summation is presented graphically in Fig-
ure 4. The polymeric hydrocarbon products exhibit the
highest oil preference and in this respect are superior to
the polymeric foam products. Results for each of the sorb-
ents are given in Tables 1-H to 5-H of Appendix H.

TABLE 14
OIL/WATER SORPTION CAPACITY RATIOS (PRODUCT AVERAGES)

| Test Oils | Bunker C | Heavy Crude | Light Crude | No. 2 Fuel | Overall Average |
|---|---|---|---|---|---|
| Test Oil Viscosity at 77° F, cs | 2800 | 2600 | 7.8 | 3.1 | |
| Inorganic | 3.3 | 2.8 | 1.4 | 1.2 | 2.2 |
| Natural Organic | 1.4 | 1.3 | 0.8 | 0.6 | 1.0 |
| Polymeric Foam | 1.6 | 1.5 | 1.4 | 1.3 | 1.2 |
| Polymeric Hydrocarbon | 6.5 | 5.4 | 3.0 | 2.6 | 4.4 |
| Miscellaneous | 2.7 | 2.5 | 1.3 | 1.0 | 1.9 |
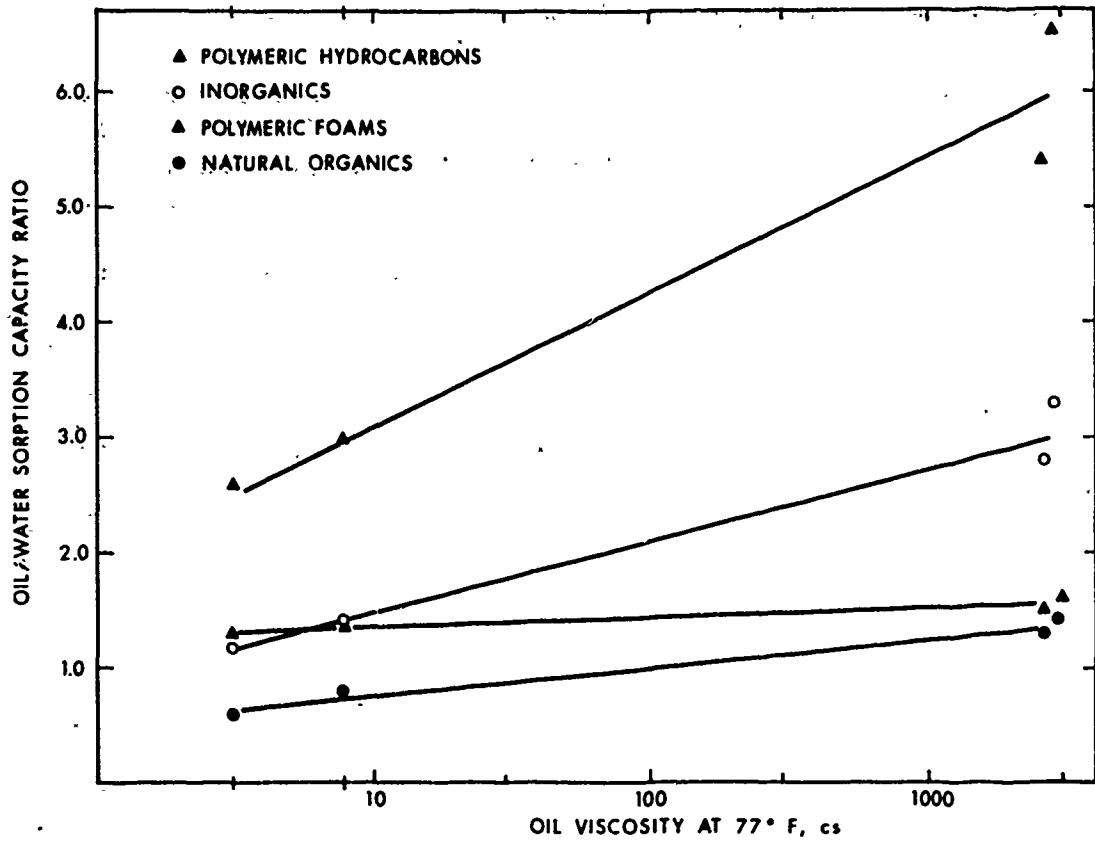
**Figure 4**
**Oil/Water Sorption Capacity Ratios**
**(Product Averages)**

OIL RETENTION

This property is determined for each sorbent with each of the four test oils. Table 15 is a summation of the percent oil retention, presented as the average of each product category for each of the four test oils. Results for each of the sorbents are given in Tables 1-I to 5-I of Appendix I. The average oil retention for sorbent structure types is presented in Table 16 for fibers, granules, powders, and foams. The only consistent trend in the data of Tables 15 and 16 is that significantly less oil is retained when the oils have a low viscosity than when they have a high viscosity, which agrees with previous results of oil sorption capacity.

## TABLE 15
### AVERAGE OIL RETENTION, %

| Test Oil, Products | Bunker C | Heavy Crude | Light Crude | No. 2 Fuel | Overall Average |
|---|---|---|---|---|---|
| Inorganic | 82 | 72 | 67 | 69 | 73 |
| Natural Organic | 80 | 81 | 53 | 43 | 65 |
| Polymeric Foam | 86 | 83 | 61 | 62 | 73 |
| Polymeric Hydrocarbon | 85 | 82 | 78 | 64 | 77 |
| Miscellaneous | 81 | 71 | 60 | 58 | 68 |
| Average (Overall), % | 81 | 79 | 63 | 57 | – |

## TABLE 16
### AVERAGE OIL RETENTION FOR SORBENT STRUCTURE TYPES, %

| Sorbent Types | Bunker C | Heavy Crude | Light Crude | No. 2 Fuel | Overall Average |
|---|---|---|---|---|---|
| Fibers | 84 | 81 | 61 | 59 | 71 |
| Granules | 75 | 76 | 59 | 50 | 65 |
| Powders | 89 | 74 | 70 | – | 76 |
| Foams | 84 | 83 | 61 | 62 | 73 |

## WATER/OIL CONTENT RATIO

This ratio is not the inverse of the oil/water sorption capacity ratio described earlier, but is a measure of the amount of water picked up and the amount of oil retained after

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shaking the oil-soaked sorbent in sea water for 6 hours.
Table 17 is a summation of the results, presented as the
average ratio of each product category for each of the four
test oils. Results for each of the sorbents are given in
Tables 1-J to 5-J of Appendix J. In Table 17 the average for
all products show the highest ratio for Bunker C oil and the
lowest for the heavy crude oil. The high value for sorbents
mixed with Bunker C oil is due to the strong tendency for
that oil to emulsify with water, resulting in a high water
pickup. Table 1 shows Bunker C oil to be a good emulsifier.
The heavy crude oil has a much lower tendency to emulsify
with water. Since it is a viscous material, a larger amount
of this oil was held by the sorbents, as previously observed.
This resulted in a low water/oil content ratio. With less
viscous oils, on the other hand, while not much water was
picked up, less oil was retained, and a higher water/oil con-
tent ratio resulted.

## TABLE 17
### WATER/OIL CONTENT RATIO AFTER SHAKING OIL-SOAKED SORBENT WITH WATER

| Test Oil, Products | Bunker C | Heavy Crude | Light Crude | No. 2 Fuel | Overall Average |
|---|---|---|---|---|---|
| Inorganic | 0.9 | 0.2 | 0.4 | 0.4 | 0.5 |
| Natural Organic | 1.2 | 0.3 | 0.7 | 1.0 | 0.8 |
| Polymeric Hydrocarbon | 1.2 | 0.2 | 0.2 | 0.2 | 0.4 |
| Polymeric Foam | 0.9 | 0.2 | 0.2 | 0.1 | 0.4 |
| Miscellaneous | 1.2 | 0.3 | 0.3 | 0.4 | 0.5 |
| All Products | 1.1 | 0.2 | 0.4 | 0.5 | |

## OIL/SORBENT COHERENCE :

This property was described in the section on Sorbent
Evaluation Methodology. It was illustrated in that section
that oil/sorbent coherence depends to a significant extent

on the nature of the petroleum product. Thus, a very viscous oil such as Bunker C will form a coherent mass with most sorbents, while No. 2 fuel does not provide much binding power. Results indicate that the oil/sorbent coherence is also affected by the ability of the oil to form water-in-oil emulsions and by the ability of the sorbent to stabilize such emulsion. This is manifested in the water/oil content ratios which are presented in Table 17. The practical consequences of the foregoing is that once oil and sorbent are properly mixed, the more viscous oils as well as those forming stable water-in-oil emulsions will provide a more coherent oil/sorbent mass while the less viscous oils, in general, will provide less coherence. The latter case would make removal of the mass from the water during an oil-spill cleanup operation more difficult.

In addition to the above observations, the ability to retain the oil/sorbent mixture on the wire screen (1/16-inch openings) during drainage provides a direct evaluation of coherence. The following materials could not be effectively retained on the screen when in all combinations with water and oils: volcanic ash, fly ash component, talc, asbestos fiber, polyethylene powder, and synthetic organic powder. The following materials could not be effectively retained on the screen when in combination with the No. 2 fuel: corn cob (ground), peanut hulls (ground), redwood fibers, sawdust, cellulose fiber-perlite mixture (A), and pine bark. All other sorbents could be effectively retained on the screen in all combinations with water and oil. The first group of materials are such fine powders that they could not be retained on the screen regardless of oil viscosity. These materials would be the hardest to remove from the water surface. Techniques for recovering oil/sorbent mixtures using screens can be expected to have mesh openings considerably larger than 1/16-inch. Consequently, other techniques would have to be applied for recovering powdery or granular sorbents.

INFLUENCE OF WATER ON OIL SORPTION CAPACITY

This property is presented as the oil sorption capacity ratio after/before shaking the sorbent with sea water for 6 hours. A ratio of 1.0 means no impairment of oil sorption capacity due to prior contact of the sorbent with water. Table 18 is a summation of the results, presented

as the average ratio of each product category for each of the four test oils. The polymeric hydrocarbon products show the least impairment of oil sorption capacity due to prior contact with water while the polymeric foam products show the most impairment. Results for each of the sorbents are given in Tables 1-K to 5-K of Appendix K.

TABLE 18
OIL SORPTION CAPACITY RATIOS AFTER/BEFORE SHAKING WITH WATER

| Test Oils, Products | Bunker C | Heavy Crude | Light Crude | Overall Average |
|---|---|---|---|---|
| Inorganic | 0.6 | 0.6 | 0.6 | 0.6 |
| Natural Organic | 0.7 | 0.6 | 0.4 | 0.6 |
| Polymeric Hydrocarbon | 0.9 | - | 0.9 | 0.9 |
| Polymeric Foam | 0.4 | 0.6 | 0.4 | 0.5 |
| Miscellaneous | 0.8 | - | 0.7 | 0.8 |
| All Products | 0.7 | 0.6 | 0.6 | - |

INFLUENCE OF WATER QUALITY ON SORBENT EFFECTIVENESS

In the section on Mechanism of the Sorption Process, it was pointed out that surface active materials accidentally or deliberately present on the water or in the oil can modify the effectiveness of sorbents by allowing water to wet and spread on them. Consequently, the use of detergents to disperse an oil spill could not realistically be followed by the use of sorbents to clean up remaining oil. The use of monomolecular piston[14] films to condense oil spills into thicker layers is a desirable initial step which would enhance the efficiency of subsequent removal procedures. Since these piston films are surface active chemicals they could interfere with the use of sorbents. A number of laboratory experiments were performed in which a light crude oil spread on water was condensed by a piston film consisting

of polyoxyethylene (4) dodecyl ether. The thickened, condensed film was easily removed from the water surface by absorbing it with a small piece of polyurethane foam B. As would be expected, when the ether compound was placed directly on the sorbent, it drove the oil away from it.

## OIL SORPTION RATES

This property was determined for some of the more promising materials. In each case a weighed piece of the material (1-x 1-x 1/2-inch thick) was placed on the surface of the oil for increasing periods of time, drained for 5 minutes and reweighed. Results are shown graphically in Figures 5a-d. For the two low viscosity test oils used (No. 2 fuel and light crude), the oil sorption rates are seen to be very rapid so that nearly the maximum capacity is attained for most sorbents in 5 minutes. For the heavy crude oil (2600 cs at 77° F) the maximum capacity for most sorbents is approached in 100 minutes. For the Bunker C oil (2800 cs at 77° F) the maximum capacity for most sorbents is approached in 1000 minutes. These data show that sorption rate is influenced much more by the viscosity of the oil than by the nature of the sorbent.
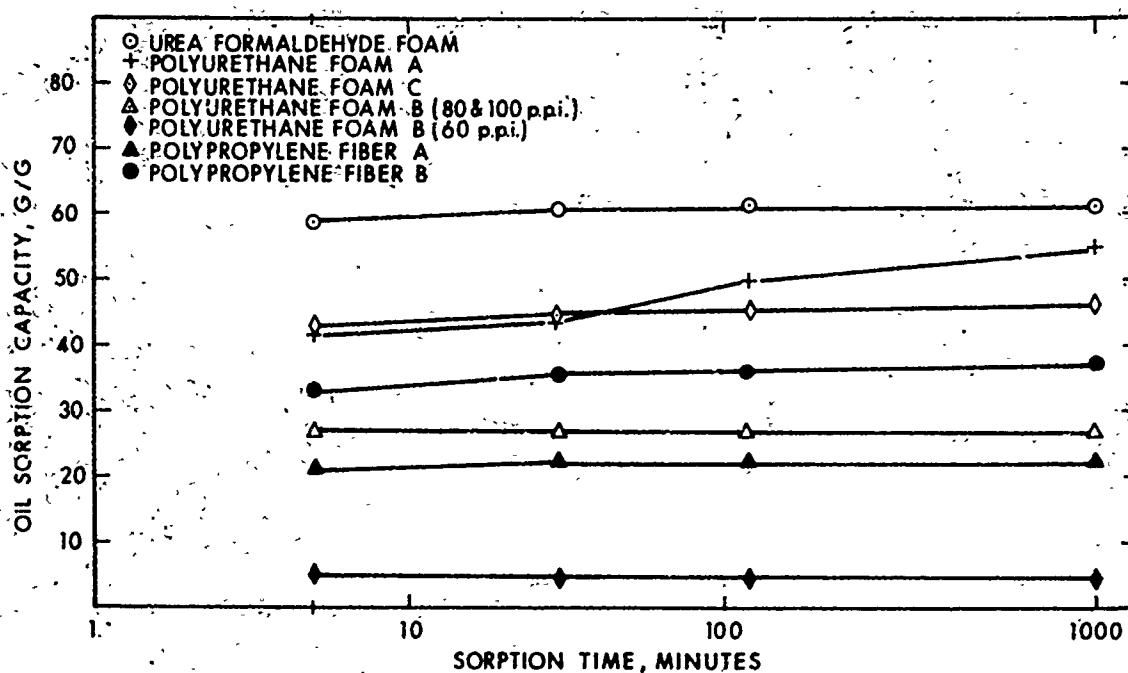


Figure 5a

No. 2 Fuel Oil Sorption Rate of Several Sorbents (77° F)

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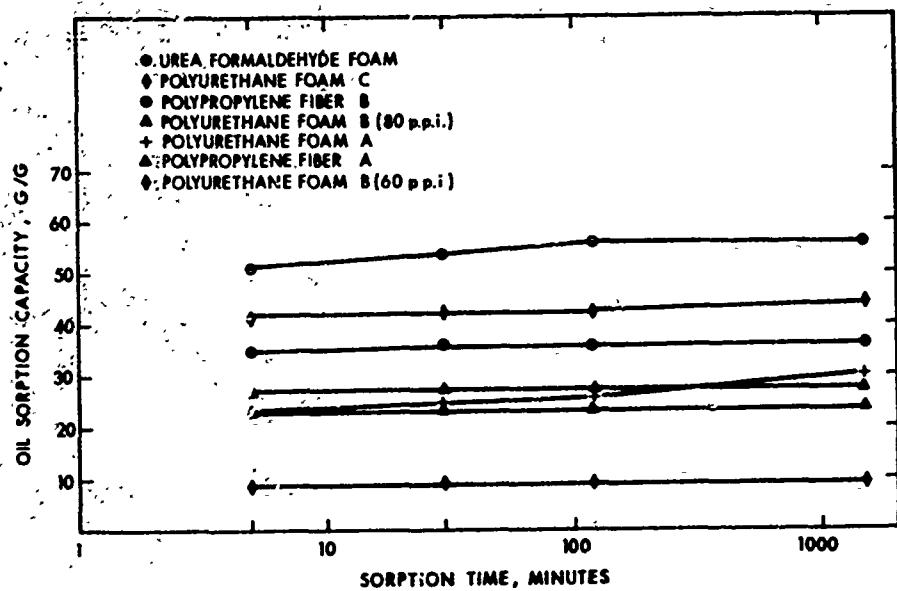
Figure 5b
Light Crude Oil Sorption Rate
of Several Sorbents (77° F)
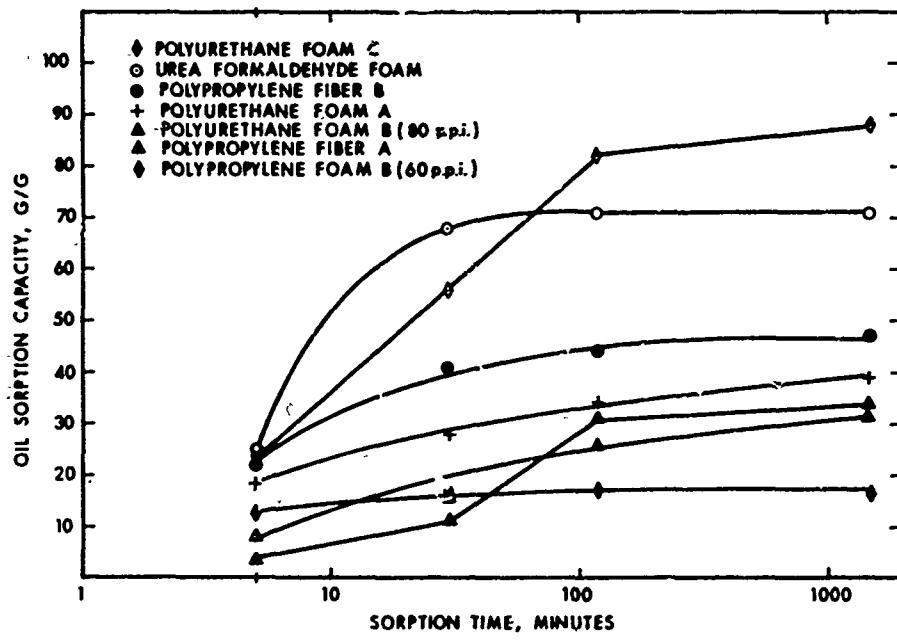


Figure 5c
Heavy Crude Oil Sorption Rate
of Several Sorbents (77° F)

32
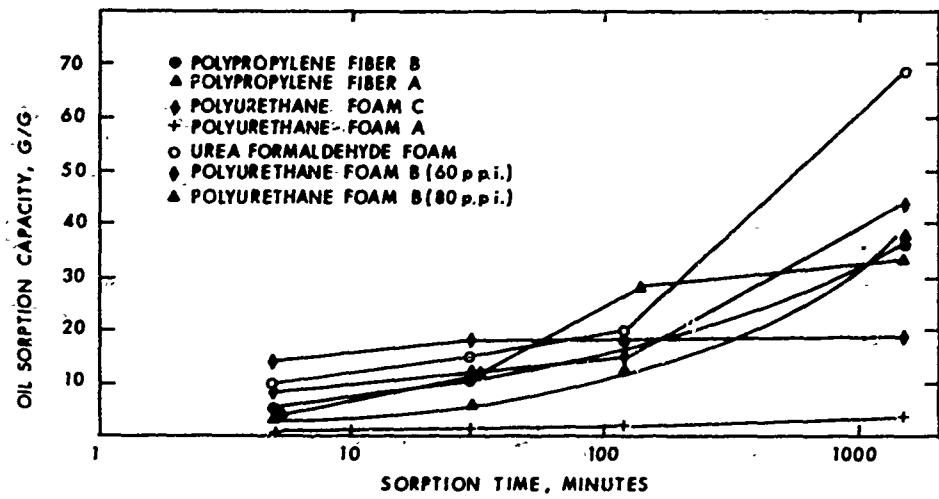
Figure 5d
Bunker C Oil Sorption Rate of Several
Sorbents (77° F)
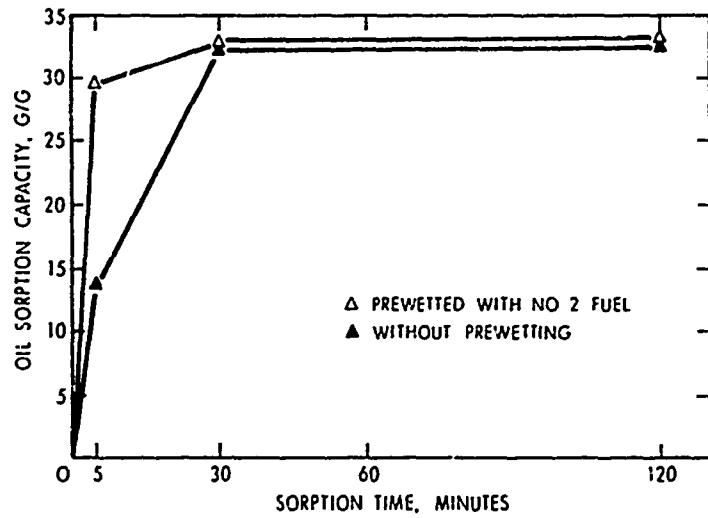


Figure 5e
Bunker C Oil Sorption Rate of Polyurethane Foam B
(80 PPI) (With and Without No. 2 Fuel Prewetting)

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The slow sorption rate for Bunker C oil can be accelerated by prewetting the sorbent with a light oil. This was done with polyurethane foam B (80 ppi). Results are shown graphically in Figure 5e. This shows that prewetting the sorbent with a light oil doubled the sorption rate for Bunker C oil during the first 5 minutes of contact with the oil.

## OIL DRAINAGE RATES

This property was determined for some of the more promising materials. A piece of the sorbent (1 x 1 x 1/2 inch) was soaked in the test oil for 1 hour, and allowed to drain on a coarse mesh screen. The oil-soaked sorbent was weighed initially and at several time intervals of draining. Results are presented graphically in Figures 6a-b. This shows that a drainage period of 15 minutes used in the test procedures is essentially adequate for the low viscosity No. 2 fuel oil and for the high viscosity heavy crude oil. In general, the results show that oil drainage rates as well as sorption rates are primarily influenced by oil viscosity rather than sorbent type.

Figure 6a

No. 2 Fuel Oil Drainage Rates
of Several Sorbents (77° F)

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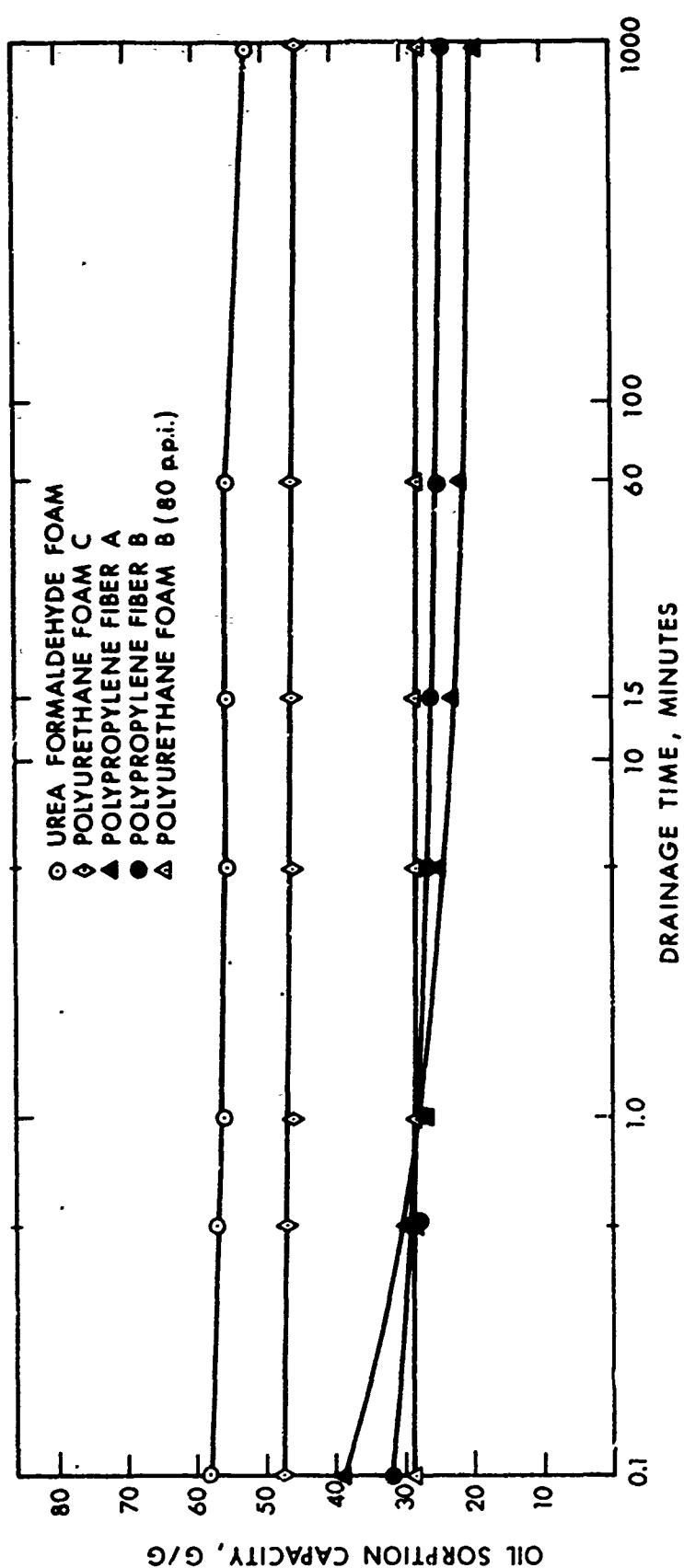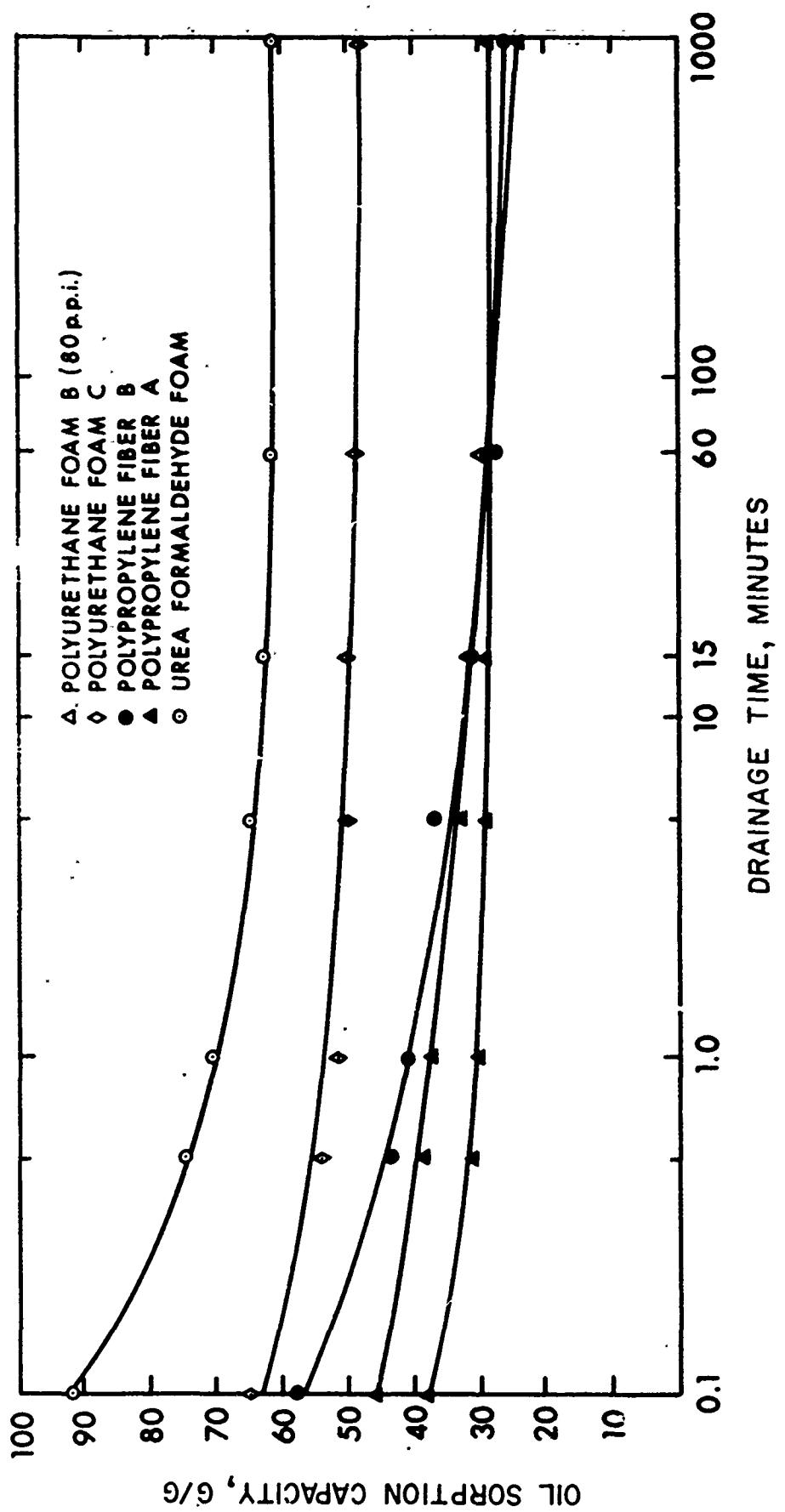
Figure 6b
Heavy Crude Oil Drainage Rates
of Several Sorbents (77° F)

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## REUSABILITY

This property was evaluated in terms of removal of the oil from the sorbent by pressing through rollers as described in Appendix A. The apparatus used is shown in Figure 3-A of Appendix A with a piece of polyurethane foam passing through the stainless steel rollers. Only those sorbents were evaluated that could be utilized in this apparatus. However, this included the most promising materials. Results for several sorbents and test oils are presented in Table 19. These results show the following:

1. Polyurethane foam (Code F-2) retains an essentially undiminished oil sorption capacity for the No. 2 fuel and the light crude oil up to 100 squeeze passes through the rollers for the same piece of material.

2. The same foam retains an essentially undiminished oil sorption capacity for the heavy crude oil up to 60 squeeze passes through the rollers for the same piece of material. After 60 cycles this material disintegrated.

3. The other materials evaluated showed either a low oil sorption capacity within 10 reuse cycles, were crushed by the rollers during the first squeeze cycle, adhered to the rollers, or could not be moved through them.

## TABLE 19
### REUSABILITY, OIL SORPTION CAPACITY, g/g

| Code | Sorbent | Test Oil | Number of Reuse Cycles (Passes through the Rollers) | | | | | | | | | | | | | | | | | | | |
|------|---------|----------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|-----|
| | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 15 | 20 | 25 | 35 | 40 | 50 | 60 | 70 | 75 | 100 |
| F-2 | PUF, B, 80 ppi | No. 2 Fuel | 28 | 27 | 27 | 28 | 27 | 28 | 28 | 29 | 27 | 28 | 29 | 29 | 28 | 24 | | 22 | | | 25 | 25 |
| | | Light Crude | 26 | 26 | 26 | 26 | 26 | | 28 | 25 | 29 | 28 | 28 | 29 | 29 | | | 28 | | | 28 | 29 |
| | | Heavy Crude | 14 | 16 | 16 | 16 | 15 | | | | | 17 | | | 17 | | 16 | 17 | 17 | ① | | |
| F-2 | PUF, B, 100 ppi | No. 2 Fuel | 27 | 27 | 25 | 25 | 27 | 27 | 26 | 27 | 27 | 27 | 27 | 27 | 27 | | | 29 | | | 27 | 26 |
| | | Light Crude | 23 | 23 | 24 | 24 | 24 | | | | | | | | | | | | | | | |
| F-3 | PUF, C | Light Crude | 39 | 35 | 43 | 42 | 41 | 38 | 37 | 36 | 35 | 34 | | | | | | | | | | |
| | | Heavy Crude | ① | | | | | | | | | | | | | | | | | | | |
| H-6 | PP fiber, bulk A | Light Crude | 25 | 17 | 8 | 12 | 10 | 11 | 13 | 11 | 9 | 11 | | | | | | | | | | |
| | | Heavy Crude | ④ | | | | | | | | | | | | | | | | | | | |
| H-7 | PP fiber, bulk B | Light Crude | 34 | 27 | 23 | 21 | 19 | 15 | 18 | 16 | 16 | 16 | | | | | | | | | | |
| | | Heavy Crude | 42 | 35 | 29 | 28 | 23 | 30 | 19 | 27 | 23 | 23 | | | | | | | | | | |
| H-8 | PP fiber (strands) | Light Crude | 6 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 5 | | | | | | | | | | |
| | | Heavy Crude | 12 | 12 | 13 | 13 | 15 | 15 | 17 | 14 | 17 | 14 | | | | | | | | | | |
| H-1 | PE fiber, continuous | Light Crude | ① | | | | | | | | | | | | | | | | | | | |
| H-2 | PE fiber sheet | Light Crude | 10 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | | | | | | | | | | |
| | | Heavy Crude | ① | | | | | | | | | | | | | | | | | | | |
| N-4 | Cellulose, wood fiber mat | Light Crude | 12 | 8 | 8 | 7 | 5 | 5 | 5 | 5 | 5 | 5 | | | | | | | | | | |

① Sorbent material disintegrated
② Sorbent crushed by rollers
③ Sorbent adhered to rollers
④ Sorbent could not be moved through rollers

PUF = Polyurethane
PP = Polypropylene
PE = Polyethylene

## MECHANICAL STRENGTH

In order to evaluate the influence of successive reuse cycles on the mechanical strength of the sorbents, some of the materials were subjected to tensile tests using an Instron machine. Results are shown in Table 20. No reduction in mechanical strength occurred as a result of 100 reuse cycles with the No. 2 fuel oil and 50 reuse cycles with the heavy crude oil.

TABLE 20
INFLUENCE OF REUSE CYCLES ON MECHANICAL STRENGTH
OF POLYURETHANE FOAM B

| Foam Pore Size | Test Oil | Reuse Cycles | Ultimate Elongation, % | UTS, psi |
|---|---|---|---|---|
| 80 ppi | ------ | 0 | 330 | 34 |
| 80 ppi | No. 2 Fuel | 25 | 420 | 42 |
| 80 ppi | No. 2 Fuel | 100 | 360 | 35 |
| 80 ppi | Heavy Crude | 50 | 320 | 34 |
| 100 ppi | ------ | 0 | 380 | 39 |
| 100 ppi | No. 2 Fuel | 25 | 350 | 40 |
| 100 ppi | No. 2 Fuel | 100 | 300 | 33 |

UTS = ultimate tensile stress

## SORBENT MORPHOLOGY

Attempts were made to study the influence of morphology on sorbent effectiveness by separating the sorbents into powders, granules, fibers, and foams as four structurally distinct categories, and using polyurethane foam B with three different pore sizes (60, 80, and 100 ppi). Table 10, page 22, illustrates that the foams are far superior in oil capacity to any of the other structure types. From Figures 5a-d, pages 31-33, it is seen that no significant difference

in oil sorption capacity exists between the 80 and 100 ppi polyurethane foams while the 60 ppi foam had a much lower capacity than either of them. The foregoing results indicate that the open-celled fine porosity resilient structure illustrated by some of the polyurethane foams is the best structure for oil sorption in terms of capacity, retention, and reusability.

## ANALYSIS AND DISCUSSION

### INORGANIC SORBENTS

This group of materials did not show adequate buoyancy retention as seen in Table 1-E of Appendix E, and the photographs in Appendix E. Only when thoroughly soaked in either the heavy crude oil or the Bunker C oil do these materials show adequate retention of buoyancy. It must be recognized that under field conditions such a thorough soaking of the sorbent with oil cannot be expected. Consequently, the uncoated portion of the sorbent could become water-logged and sink, taking the oil-coated portion with it. The relatively poor buoyancy retention shown by the inorganic sorbents occurred despite surface treatment of some of these materials to make them hydrophobic. It appears, therefore, that the treatment was only partially effective. In the case of the perlite, vermiculites A and B, and the volcanic ash, the fine components which sank may not have been expanded as the rest of these materials were, resulting in densities substantially greater than that of water. The expanded inorganic sorbents remain afloat due to air trapped in the material's interstices. This air can be displaced by the low viscosity water (unless the surface is adequately hydrophobic) or low viscosity oils resulting in a substantial increase in average density. Some products can be made buoyant by placing them in bags consisting of buoyant materials or by adding floatation pieces to the bag. The mesh size of such a bag must be made small enough to keep sorbent particles from escaping and large enough to permit easy access to the sorbent by viscous oil slicks.

### NATURAL ORGANIC SORBENTS

These materials consist of vegetable fibers in one form or another. They have poor buoyancy retention as seen in

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Table 2-E of Appendix E and the photographs in Appendix E. Table 7, page 18, shows that the natural organic sorbents have the lowest buoyancy retention of all the sorbent categories. As in the case of the inorganic sorbents, consistently adequate buoyancy could only be obtained when these materials were soaked with heavy crude or Bunker C oil. Oil sorption capacity for the natural organic sorbents is only slightly higher than the inorganic materials as seen in Figure 3, page 20. The natural organic sorbents have the lowest oil/water capacity ratio (oil preference) as seen in Table 14, page 25, and Figure 4, page 26. This indicates that these materials are not sufficiently hydrophobic to be effective for removing oil slicks from water. In general, this group of materials has poor buoyancy retention and a relatively low oil sorption capacity. Consequently, they do not appear attractive for oil spill cleanup purposes.

Straw, which is a member of this group of materials, has received much attention and use for cleaning up oil spills. This is due primarily to its availability and the primitive state-of-the-art of cleaning up oil spills with sorbents. The use of straw under field conditions does not constitute an adequate evaluation of its effectiveness nor should such use be considered an endorsement. No measure is made of how much of the spilled oil is dissipated by natural forces nor how much of the distributed straw has sunk. The relatively low oil sorption capacity of straw is illustrated in Figure 3, page 20, where straw is shown in comparison to other materials. Aside from its inherently poor buoyancy characteristics, the low oil sorption capacity of the straw would require the transportation, distribution, collection, and disposal of much larger quantities of materials than would be the case for sorbents having higher oil pickup capacities. This specific limitation also applies to both the inorganic and natural organic sorbent materials. Neither of these two groups show any significant potential for reuse; that is, repeated on-site separation of oil from sorbent and consequent reuse of sorbent.

## MISCELLANEOUS SORBENTS

This group consists of materials that do not belong to any of the other groups. Members of this group lack adequate buoyancy retention or oil sorption capacity or both as seen in Table 5-E of Appendix E and Table 5-F of Appendix F. In

this respect, this group of sorbents does not differ significantly from the inorganic and natural organic materials. One member of this group, a synthetic organic powder (Code M-8) appears to have a high capacity for Bunker C oil, but this drops off rapidly for the other test oils (Table 5-F of Appendix F). This material appears to function more as a thickening or gelling agent than as a sorbent.

While most of the sorbent materials examined have some utility in removing oil spilled on water, the inorganic, natural organic, and miscellaneous sorbents demonstrated such inadequate buoyancy, retention and low oil sorption capacity that they rank far behind the polymeric foam and polymeric hydrocarbon sorbents in those two basic properties. Consequently, further discussion will concentrate on the latter two sorbents.

POLYMERIC FOAM SORBENTS

This group consists of three polyurethane and one urea formaldehyde foam. These materials have very good buoyancy retention and a very high oil sorption capacity as shown in Tables 3-E of Appendix E and 3-F of Appendix F, respectively. Unfortunately, they also have a high capacity for absorbing water when preferentially contacted, which impairs their capacity for sorbing oil. The relatively high water-sorption capacity of the foams is illustrated in Table 12, page 24. This results in the relatively low oil/water sorption capacity ratio of Table 14, page 25, and Figure 4, page 26. Table 18, page 30, shows the foams to have the greatest impairment in oil sorption due to prior contact with water of all the materials evaluated. While this is an undesirable property it is counterbalanced by the very high capacity for oil exhibited by these sorbents. Resilient polyurethane foams have good reusability characteristics as seen in Table 19, page 38. After the first wring-squeeze cycle the foam retains a coating of oil which makes the material more hydrophobic and oleophilic. It appears, that the relatively poor resistance to wetting by water exhibited by foams can be partially overcome in those cases where the foam can be reused (recycled).

Of the four foams evaluated, the urea formaldehyde appears the least promising. While it has a high capacity for oil it also absorbs more water than any of the foams

(Table 3-G of Appendix G). Its oil sorption capacity is the most impaired of the foams by prior contact with water (Table 3-K of Appendix K). The urea formaldehyde foam has no significant reuse potential since if has a fragile, brittle structure. When passed through the wringer type rollers used in the reusability tests, it is crushed. Its weak mechanical strength is also demonstrated in the 6-hour shaking test with water. Considerable amount of fine debris was generated which became water-logged and sank. Similar limitations apply to polyurethane foam A which is a semi-rigid material. This foam was used in the shredded form for its evaluation. It does not have reuse potential since it crushed easily.

Polyurethane foams B and C demonstrate a good reuse potential as seen in Table 19, page 38. Both foams performed well with the low viscosity oils. Foam B (80 and 100 ppi) showed no reduction in oil sorption capacity for 100 reuse cycles and no reduction in mechanical strength, Table 20, page 39. When using the viscous heavy crude oil, foam C could not be recycled and foam B lasted for 60 reuse cycles before disintegrating, although 50 reuse cycles showed no loss in mechanical strength. The lesser reuse performance with the heavy crude oil is due to the greater slippage in the rollers occurring with this more viscous oil. This results in more shear forces acting on the foam so that it gradually disintegrates or is crushed.

A unique characteristic of the foams as a category of sorbents is that they have a distinct cellular structure (matrix) which does not depend on the viscous nature of the oil to provide coherence of the oil/sorbent mixture. None of the other sorbents have this characteristic although some of the polymeric hydrocarbon fibers appear to approach it.

POLYMERIC HYDROCARBON SORBENTS

These materials have the best buoyancy characteristics (Table 4-E of Appendix E), they are the most hydrophobic and oleophilic of the sorbents as manifested in their highest average oil/water capacity ratio (Table 14, page 25, Figure 4, page 26, Table 4-H of Appendix H) and they are the least impaired in oil sorption capacity by prior contact with water, Table 18, page 30. In these respects they are

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superior to the polymeric foams. However, they lack the capacity for oil exhibited by the foams. The polymeric hydrocarbon sorbents exhibit average oil sorption capacities that range from one-third to less than half of the foam products. By considering only the nonwoven fibers in Table 4-F of Appendix F, the average oil sorption capacities would range from approximately half to two-thirds of the foams. Thus, the foams still have significantly superior oil sorption capacities.

Some of the polypropylene fibers show a potential for reuse, Table 19, page 38. In general, this does not appear to be as good as the resilient polyurethane foams. This may be because the collection of fibers do not have a distinct structure as the foams which can be compressed and will return to their original dimensions upon release of the pressure. Of the polymeric hydrocarbon sorbents, the polypropylene fibers appear to be the most promising materials for further consideration. A foam made of polyethylene or polypropylene could be a sorbent superior to all the materials evaluated.

## SUMMARY

Laboratory methods to evaluate floating sorbents for removing oil spilled on water were developed. Forty-nine different sorbent materials were evaluated with these methods. The sorbents were separated into the following categories: inorganic, natural organic, polymeric foam, polymeric hydrocarbon, and miscellaneous sorbents. Each of the four specific categories contained enough members so that conclusions drawn about each group would apply to sorbents not tested but belonging to one of these groups. Laboratory procedures were utilized to determine buoyancy characteristics, oil and water sorption capacity, oil retention, oil/sorbent coherence, and influence of prior contact with water on a sorbent's oil sorption capacity. Additional tests conducted were oil sorption and drainage rate, reusability, and mechanical strength.

Buoyancy retention tests showed the polymeric foam and the polymeric hydrocarbon sorbents to be the best. Relatively poor buoyancy retention was shown by the inorganic, natural organic, and miscellaneous sorbent materials although one or two members of these groups had adequate buoyancy retention.

Oil sorption capacity tests showed the polymeric foams to have the highest capacity, the average for the four different test oils used ranging from 47 to 62 grams of oil per gram of sorbent. The polymeric hydrocarbon sorbents showed averages ranging from 14 to 28 grams/gram. For the three remaining groups these values were: inorganic sorbents (3 to 9 g/g), natural organic sorbents (5 to 11 g/g), and miscellaneous sorbents (4 to 12 g/g).

Comparisons of oil sorption capacity test results were made with results available from two other laboratories. Very good agreement was found in most cases.

Water sorption capacity tests showed that the polymeric foams have by far the highest capacity of all the sorbents, which is an undersirable property since it indicates poor resistance to wetting by water. Prewetting the foams with a light oil may enhance their resistance to wetting by water.

The oil/water capacity ratio can be calculated from the previous two properties and is a measure of the material's preference for oil relative to water. The highest ratio by far was exhibited by the polymeric hydrocarbon products.

Oil retention is a measure of the sorbent's ability to hold the oil. Results show that this property is more a function of the oil's viscosity than the nature of the sorbent. Thus, the highest oil retention for all sorbents occurred with the most viscous oils while the lowest retention was found with the low viscosity test oils.

Water/oil content ratio is a measure of the amount of water picked up and the amount of oil retained by a sorbent after shaking the oil-soaked sorbent in sea water for 6 hours. A low ratio is desirable. Results show that relatively high ratios occurred when the Bunker C test oil was used, due to that oil's tendency to emulsify with water. Powdery or granular sorbents tended to stabilize such emulsion. The much lower emulsion-forming tendency of the heavy crude test oil resulted in lower ratios.

Oil/sorbent coherence is related to the ability to remove the mass from the water surface. This property is also primarily a function of the test oil viscosity, the more viscous oils resulting in greater coherence. A number of sorbents, however, due to their small particle size cannot

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be retained on a screen regardless of the viscosity of the test oil with which they have been soaked.

The influence of water on oil sorption capacity is expressed by the oil sorption capacity ratio after/before shaking the sorbent with sea water for 6 hours. A ratio of 1.0 means no impairment of oil sorption capacity due to prior contact of the sorbent with water. Results show that the least impairment is shown by the polymeric hydrocarbon sorbents and the most impairment by the polymeric foam sorbents.

Reusability (recycling) of sorbents by on-site separation of the oil and redistributing the sorbent on the oil slick is one of the most important, if not the key, property of sorbents. The resilient polymeric foams demonstrated the best reuse characteristics of all the sorbents evaluated.

## CONCLUSIONS

The laboratory methods developed in this investigation for evaluating sorbents are satisfactory and the results can be applied to the selection of sorbents for full-scale sorbent dispersal and recovery systems.

The polymeric foams are the best materials currently available for oil spill cleanup. Of these, the resilient polyurethane foams show the best overall sorbent properties despite their high capacity for water which impairs their capacity for oil. The superiority of the foams lies in their high oil sorption capacity and high reuse (recycling) potential.

The polymeric hydrocarbon materials show very good qualities as sorbents. Of these, the polypropylene fiber materials show the best potential.

The inorganic sorbents and natural organic (vegetable origin) sorbents are not recommended due to their relatively low oil sorption capacity and buoyancy retention. They do not demonstrate significant reuse potential.

Each of the four material categories contained enough members so that the conclusions drawn are applicable to materials not evaluated, but belonging to these categories.

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## RECOMMENDATIONS

This report has presented a large amount of data on many different types of oil sorbent materials. It is expected that this information is sufficient to establish an ordered understanding of the essential properties of the many different sorbent materials that could be used in cleaning up oil spills. Based on the results presented a number of recommendations for future effort can be made:

- Sorbents combining the high oil-sorption capacity and good reusability of the resilient, open-cell polyurethane foams with the low affinity for water of the polymeric hydrocarbons should be identified and investigated. An example of such a material would be a polypropylene foam.

- Consideration should be given to increasing the hydrophobicity of the polyurethane foams, possibly by modifying the formulation process.

- Scale-up investigations should be conducted which combine the use of sorbents with the use of monomolecular piston films to condense oil slicks, examine the influence of slick thickness on sorbent efficiency, and determine the relationship between natural mixing energy (from waves and wind), and necessary sorbent/oil contact time.

- Special techniques should be developed for sorbent distributing, recovery, and reuse with emphases placed on utilization of existing equipment and training of available manpower.

## ACKNOWLEDGMENT

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Appendix A
Laboratory Procedures for Evaluating Sorbent Materials

# 1. Scope.

1.1 The procedures cover: determination of the maximum oil sorption capacity of the dry sorbent and the oil retention after water washing the oil-soaked sorbent; determination of the water sorption capacity of the dry sorbent and oil sorption capacity of the water-saturated sorbent; sorbent buoyancy characteristics; and sorbent reusability.

1.2 The procedures cover sorbent materials independent of their morphology; that is, whether they are powdery, granular, fibrous, have a porous matrix or any combination of these.

1.3 The procedures may be conducted at any selected temperature, as long as the oil remains liquid.

# 2. Summary of Method.

2.1 The oil sorption capacity of the dry sorbent is determined on a weighed sorbent sample which is then saturated with oil, drained and weighed.

2.1.1 Oil retention of the sorbent after water washing is determined on the above sample. The oil-soaked sorbent is shaken in sea water (buoyancy behavior is noted) and the sample is filtered, drained, and weighed. (The weight is corrected for absorbed water.)

2.2 The water sorption capacity of the dry sorbent is determined on a weighed sorbent sample by shaking with sea water (buoyancy behavior is noted); and the sample is filtered, drained, and weighed.

2.2.1 Oil sorption capacity of the water-saturated sorbent is determined on the above sample by saturating it with oil, draining, and weighing. (The weight is corrected for absorbed water.)

2.3 Buoyancy characteristics are determined qualitatively by observations made in the procedures for 2.1.1 and 2.2. For quantitative measurements of oil-free sorbent buoyancy or oil-soaked sorbent buoyancy, a weighed sample of the dry or oil-soaked sorbent is shaken with sea water and allowed to stand until settling of equilibrium has occurred; the

floating sorbent is decanted, filtered, drained, and weighed (the weight is corrected for absorbed water and oil). The sunken sorbent is filtered, drained, and weighed (corrected for absorbed water and oil), and the sorbent buoyancy calculated.

2.4 Sorbent reusability is determined by saturating a weighed sample of the sorbent with oil and pressing the oil from the sorbent between rollers. This process is repeated until either sorbent disintegration occurs or oil sorption capacity is lost.

3. Apparatus.

3.1 Screen basket - A wire screen basket made of brass or other corrosion resistant metal having 1/16-inch (1.6mm) openings, 3-inch-diameter (76 mm) and 1 1/2-inch-depth (38 mm) with a wire handle for suspension purposes. (See Figure 1-A.)
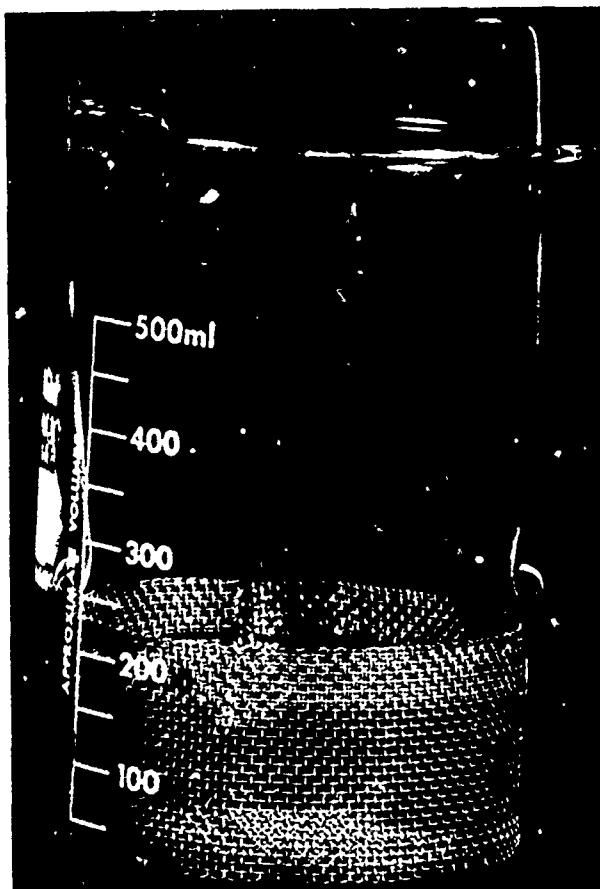


Figure 1-A
Screen Basket

3.2 Sieve - 100 mesh nylon monfilament cloth with openings 0.15 mm. Size and uniformity of mesh is covered by ASTM Specification E11-58T. Obtained as Sieve Set, catalog number 3536 from Spec Industries, Inc., P. P. Box 798, Metuchen, New Jersey 08840.

3.3 Beakers - Approximately 600 ml, within which the wire screen basket (paragraph 3.1) fits.

3.4 Bottle - Glass, wide mouth, 1000 ml capacity, takes rubber stopper number 11 1/2.

3.5 Shaking apparatus - Reciprocating motion at an amplitude of 1.1 to 1.2 cm, frequency of $140 \pm 10$ cycles per minute. Possible supplier - Precision Scientific Company, catalog number 66802. (See Figure 2-A.)
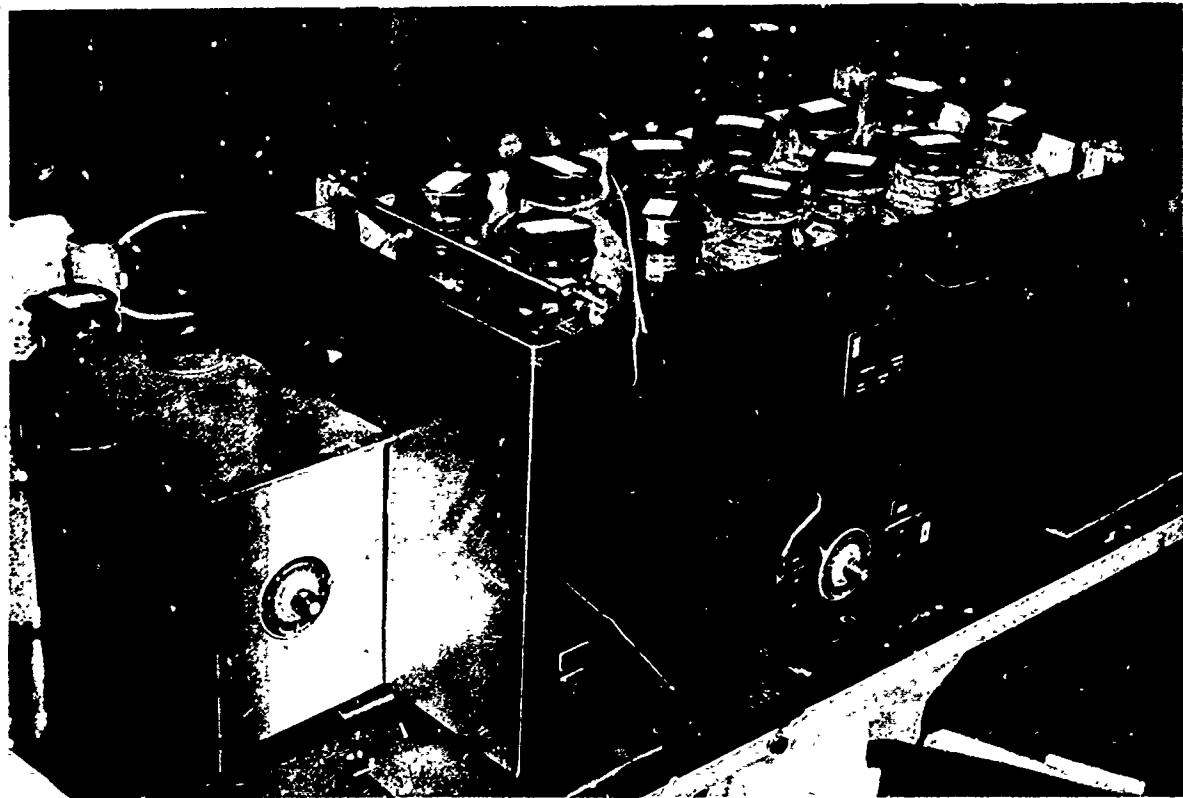


Figure 2-A
Shaking Apparatus

3.6 Sorbent reusability test apparatus.- (see Page 37) is described as "Noodle Chef" with 8 adjustments, 6-inch rollers, chromeplated steel, table clamp. Possible supplier is Sears Roebuck and Company, Philadelphia, Pennsylvania 19132. The adjustable gap between the rollers ranged from 0.015 to 0.06 inch. It is manually operated. (See Figure 3-A.)
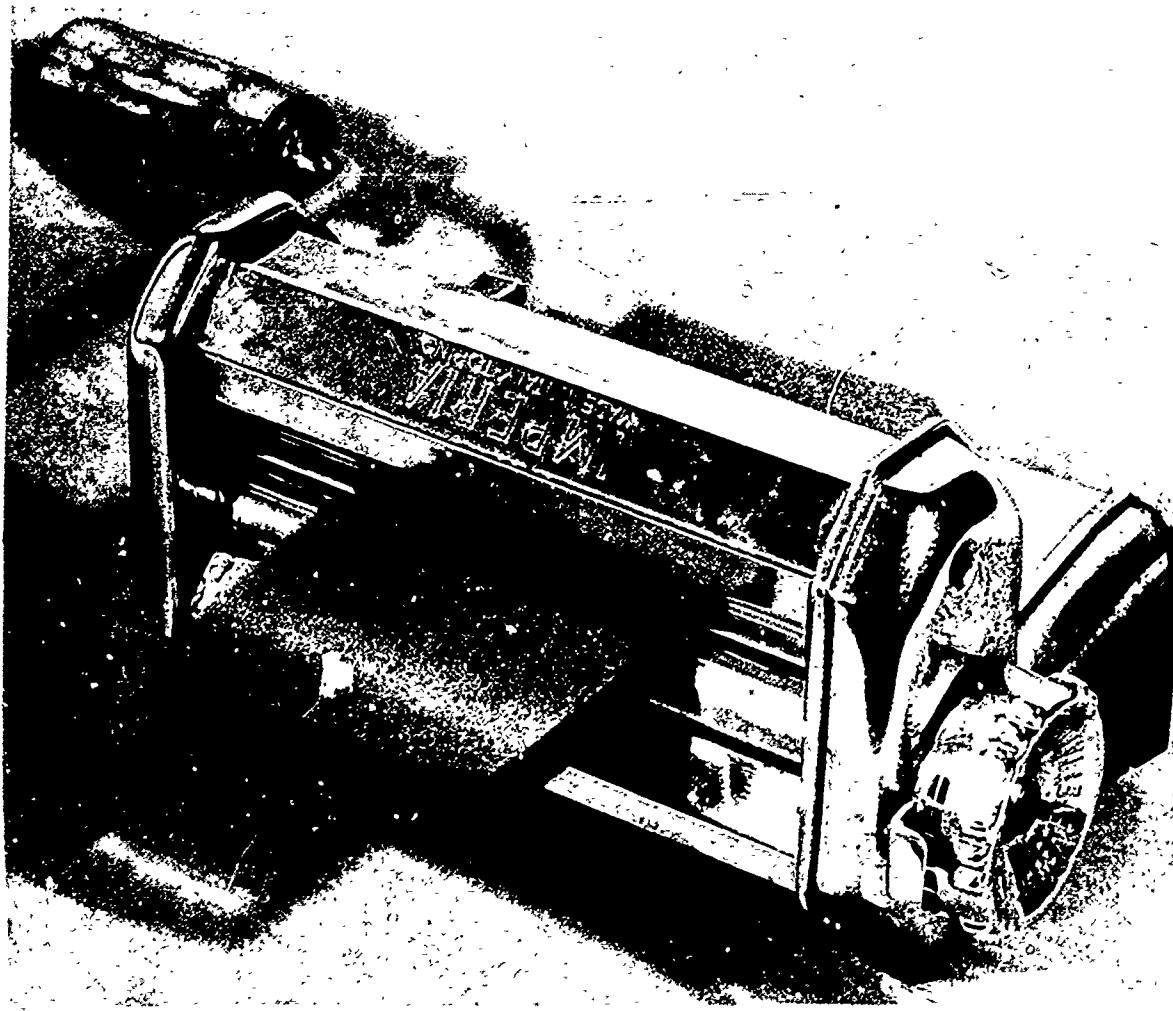


Figure 3-A
Reusability Test Apparatus

## 4. Reagents.

4.1 Synthetic sea water prepared according to ASTM method D665-60 (Reapproved 1968).[1]

## 5. Procedure A.

Oil Sorption Capacity of Dry Sorbent and Oil Retention After Water Washing Oil-Soaked Sorbent.

### 5.1 Oil Sorption Capacity of Dry Sorbent

Weigh a sufficient quantity of dry sorbent to fill the screen basket half full. If, upon agitation, using a sifting action, more than 5% of the sorbent passes through the screen, weigh the nylon sieve half full of sorbent and place it in the screen basket. Lower the basket (or basket containing the sieve) with the sorbent into the 600 ml beaker and add sufficient oil (at 77° F or other desired temperature) down the side of the beaker to fill the basket or sieve to within a fraction of the top (allowing sufficient space for stirring the oil-sorbent mixture without loss out of the basket or the sieve). Stir gently with a stirring rod during the 15 minutes soaking period. Raise the basket and secure on a rack above the beaker for a drainage period of 15 minutes. If the sieve is used, place the tip of a stirring rod in contact with the interior bottom of the sieve to assist draining. Using a spatula, transfer the contents of the material remaining within the screen or sieve onto a tared watch glass, obtain the weight of the oil-soaked sorbent and calculate the oil sorption capacity. Retain the oil-soaked sorbent and proceed as in 5.2.

### 5.2 Oil Retention After Water-Washing Oil-Soaked Sorbent.

Transfer the weighed oil-sorbent mixture from 5.1 into a 1000 ml bottle containing 500 ml of synthetic sea water. Seal the container with a rubber stopper. Shake the mixture for 6 hours in the shaking apparatus. Allow the mixture to

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[1] 1971 Annual Book of ASTM Standards, "Petroleum Products- Fuels, Solvents, Lubricating Oils, Cutting Oils, Grease," Part 17.

settle and make a visual estimate of the buoyancy characteristics based on the amount of sorbent which sinks and which floats.[1] Decant the oil-sorbent-water mixture through the screen basket, collecting drainings in a clean beaker. Allow 15 minutes for drainage. If some of the oil and water-soaked sorbent passes through the screen, then filter this portion through the nylon sieve. Transfer the oil and water-soaked sorbent from the basket and from the nylon sieve onto a tared watch glass and record the weight. Determine the amount of oil and water in the oil and water-soaked sorbent as follows. Place all, or a measured portion of the mixture, into an ASTM D95-70 Water by Distillation Apparatus[2] and determine water content as described. Record the quantity of water as grams picked up per gram of sorbent. Calculate the amount of oil by difference from the total weight of oil and water-soaked sorbent by substracting from it the sum of the sorbent plus water weights. Calculate the sorbent oil retention.

## 6. Procedure B.

Water Sorption Capacity of Dry Sorbent and Oil Sorption Capacity of Water-Saturated Sorbent.

### 6.1 Water Sorption Capacity of Dry Sorbent.

Weigh a sufficient quantity of sorbent to fill the nylon[3] sieve half full. Place the weighed sorbent contents of the sieve into a 1000 ml bottle containing 500 ml of synthetic sea water and seal with a rubber stopper. Shake the mixture for 30 minutes on the shaking apparatus. Allow the mixture to settle and make a visual estimate of the buoyancy characteristics based on the amount of sorbent which sinks

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[1] If quantitative measurement of buoyancy is required, turn to paragraph 7 at this point.

[2] 1971 Annual Book of ASTM Standards, "Petroleum Products - Fuels, Solvents, Lubricating Oils, Cutting Oils, Grease," Part. 17.

[3] The nylon sieve is used in lieu of the screen basket because there is no problem in passing water through the sieve and the procedure is equally good for coarse or fine sorbents.

and that which floats.[1] Decant the contents of the bottle through the nylon sieve, washing the sorbent from the bottle with synthetic sea water. Drain 5 minutes and transfer the contents onto a tared watch glass. Record the weight and calculate the water sorption capacity of the dry sorbent. Retain the water-soaked sorbent and proceed as in 6.2.

## 6.2  Oil Sorption Capacity of Water-Saturated Sorbent.

Transfer the water-soaked sorbent from 6.1 to the screen basket. If greater than 10% of the water-soaked sorbent passes through the screen basket, use the nylon sieve within the screen basket. Lower the basket and contents into a 600 ml beaker and gently fill the screen basket or sieve with oil to within a fraction of the top. Stir gently with a glass stirring rod during a 15-minute soaking period.

Raise the basket and secure on a rack above the beaker for a drainage period of 15 minutes. If the sieve is used, place the tip of a stirring rod in contact with the interior bottom of the sieve to assist draining. Using a spatula, transfer the contents of the material remaining within the screen or sieve onto a tared watch glass and obtain the weight of the oil absorbed on the wet sorbent. Obtain water content by distillation (ASTM D 95-70) on all or a portion of the oil-water-sorbent mixture. Record the grams of water obtained and calculate the amount of oil in the oil-water-sorbent mixture by difference. Calculate the oil sorption capacity of the wet sorbent.

## 7.  Procedure C.

Buoyancy Characteristics of Dry Sorbent and of Oil-Soaked Sorbent.

### 7.1  Buoyancy of Dry Sorbent

Proceed as in paragraph 6.1 for Water Sorption Capacity of Dry Sorbent up to the point indicated by footnote 1, at the bottom of this page. If any of the sorbent is still

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[1] If quantitative measurement of buoyancy is required, go to paragraph 7 at this point.

buoyant, after the 30-minute shaking period, extend the
shaking time to 6 hours.

After shaking, fill the 1000 ml bottle with synthetic
sea water and allow the mixture to settle. Gently decant the
floating material onto the screen basket, collecting the
filtrate[1] in a beaker. Repeat the sea water filling, settling,
and decanting until all the floating material has been
collected. Allow 5 minutes for drainage of water from the
sorbent collected on the sieve and transfer the contents onto
a tared watch glass. Weigh and record the grams of floating
water-soaked sorbent material. Correct this weight for water
content by ASTM D 95-70.

Next, transfer the sunken sorbent material to the sieve
using sea water as a flushing medium. Transfer material
from sieve onto a tared watch glass. Weigh and record grams
of sunken water-soaked sorbent. Correct this weight for
water content by ASTM D 95-70.

7.2  Buoyancy of Oil Soaked-Sorbent

Proceed as in paragraph 5.2 for Oil Retention After
Water-Washing Oil-Soaked Sorbent to the point indicated by
footnote 1, page A-6.

Fill the 1000 ml bottle with synthetic sea water and
allow mixture to settle. Gently decant the floating mixture
onto the screen basket, collecting the filtrate[1] in a clean
beaker. Repeat the sea water filling, settling, and decant-
ing steps until all floating material has been collected.
Allow 5 minutes for drainage of water from the sorbent
collected on the screen and transfer onto tared watch glass.
Weigh and record grams of floating oil-water-soaked sorbent
material. Correct this weight for water content by ASTM
D 95-70 and for oil content by washing the ASTM D 95-70 distil-
lation residue with additional solvent and weighing the washed
residue after drying.

Next transfer the sunken sorbent material to the screen
using sea water as a flushing medium. Scrape material from

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[1]If observation of the filtrate indicates appreciable sorbent
is passing through the screen, substitute the nylon sieve
for the screen basket.

screen onto tared watch glass. Weigh and record grams of sunken oil-water-soaked sorbent. Correct this weight for water content by ASTM D 95-70 and for oil content by treating the distillation residue as above.

8. **Procedure D.**

Sorbent Reusability.

Weigh a piece of sorbent sheet[1] of desired size as determined by the length of the rollers on the sorbent reusability test apparatus. Set the roller gap distance to the smallest distance that permits the oil-soaked sorbent to move freely through the rollers.

Saturate the sorbent with oil in an open flat pan by completely covering the sorbent with oil. After soaking 15 minutes gently slide the oil-soaked sorbent onto a flat wire screen (maintaining a horizontal position to prevent improper drainage) and allow to drain for 15 minutes. Slide the drained oil-soaked sorbent onto a tared flat pan (aluminum sheet). Weigh the oil-soaked sorbent and determine amount of oil absorbed. Remove the oil by passing the oil-soaked sorbent through the rollers. Again weigh the sorbent and determine the oil retained and/or the oil removed on pressing. Continue the soaking, draining, weighing, pressing, and weighing until the sorbent disintegrates or its oil sorption capacity decreases.

9. **Calculations.**

9.1 **Procedure A.**

9.1.1 Oil Sorption Capacity of Dry Sorbent

$$\frac{(oil + sorbent, g) - (dry\ sorbent, g)}{dry\ sorbent, g}$$

= g oil/g dry sorbent

---

[1]For sorbents not available in sheets, a cloth container or pieces of sorbent joined by sewing can be used.

9.1.2 Oil Retention After Water-Washing Oil-Soaked Sorbent.

$$\frac{(oil + sorbent + water, g) - (dry\ sorbent, g) - (water, g)}{dry\ sorbent, g}$$

= g oil retained/g dry sorbent

9.2 Procedure B.

9.2.1 Water Sorption Capacity of Dry Sorbent.

$$\frac{(water + sorbent, g) - (dry\ sorbent, g)}{dry\ sorbent, g}$$

= g water/g dry sorbent

9.2.2 Oil Sorption Capacity of Water-Saturated Sorbent.

$$\frac{(oil + sorbent + water, g) - (dry\ sorbent, g) - (water, g)}{dry\ sorbent, g}$$

= g oil/g dry sorbent

10. Precision.

10.1 Repeatability.

Repeatability of the measurement of oil sorption capacity was assured by performing a number of duplicate and triplicate determinations on 20 sorbent materials using four test oils. Test results on these 20 sorbents were presented in a technical paper.[1] For each set of replicates, the deviation from the average was determined and expressed as percent precision. The overall average precision was determined from 80 sets of replicates shown in appendix B. This analysis shows that the

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[1]Schatzberg, P., and K. V. Nagy "Sorbents for Oil Spill Removal," Proceedings of Joint Conference, Prevention and Control of Oil Spills, Sheraton Park Hotel, Washington, D. C., June 15-17, 1971.

A-10

overall average precision is ±5%. This is considered good
for the evaluation of sorbents since it adequately distin-
guishes effectiveness between different materials.

10.2 Reproducibility - not yet established.

Appendix B
Replicate Measurements

TABLE 1-B

MAXIUM OIL SORPTION CAPACITY, GRAMS OIL GRAM SORBENT

| Code | Test Oils | Bunker C | Heavy Crude | Light Crude | No. 2 Fuel |
|---|---|---|---|---|---|
| | Test oil viscosity at 77°F, cs | 2800 | 2600 | 7.8 | 3.1 |
| I-4 | Perlite | 4.9,4.2 | 4.1,3.9 | 3.3,3.4 | 3.0,3.0 |
| I-6 | Vermiculite A | 4.9,3.7 | 3.8,3.7 | 3.5,3.1,3.4 | 3.6,3.6 |
| I-8 | Volcanic Ash | 19.5,22.8 | 16.4,18.0,20.0 | 7.1,7.4 | 5.2,4.8 |
| N-1 | Corn Cob, Ground | 5.7,5.6 | 5.8,5.3 | 5.0,4.7,4.3 | 3.9,3.7 |
| N-7 | Peanut Hulls, Ground | 6.5,5.1 | 4.0,4.6 | 2.3,2.1 | 2.2,2.1 |
| N-11 | Redwood Fiber, Shredded | 14.7,14.8 | 12.5,11.1 | 6.5,6.4 | 6.4,6.3 |
| N-12 | Sawdust | 4.1,3.9 | 3.5,3.9 | 3.9,3.4 | 2.8,2.9 |
| N-13 | Straw, Wheat | 6.0,5.5 | 6.4,6.3 | 2.7,2.0 | 1.8,1.8 |
| N-3 | Cellulose, Wood fibers | 18.5,18.7 | 17.4,17.2 | 11.1,11.6 | 9.7,8.3 |
| | Polyurethane Foams | | | | |
| F-1 | A. Polyether, Shredded | 66.4,79.0 | 82.2,64.0,78.2 | 61.2,58.8 | 55.0,42.4 |
| F-2 | B. Polyester, Reticulated | 31.6,29.0 | 25.1,24.6,23.7 | 30.9,30.4,30.5 | 27.9,28.0,26.6 |
| F-3 | C. Polyether, 1/2-inch cubes | 74.4,72.0,72.4 | 72.0,68.0,75.0 | 65.0,67.2 | 65.2,64.8,64.6 |
| F-4 | Urea Formaldehyde Foam | 76.2,69.2 | 57.0,51.8,48.3 | 50.8,47.4,52.6 | 49.8,42.2,51.4 |
| | Polyethylene Fibers | | | | |
| H-3 | A. Loose | 39.7,34.3 | 26.3,29.3 | 19.2,20.2 | 18.1,15.3,14.9 |
| H-2 | B. Sheet, Matted | 19.3,17.9 | 16.0,19.2 | 12.2,11.6 | 11.1,10.6,10.1 |
| H-1 | C. Continuous | 43.0,49.0 | 33.4,40.0 | 43.6,47.2 | 36.6,35.8 |
| H-8 | Polypropylene Fiber Strands | 21.5,21.9 | 17.4,17.2,19.8 | 7.1,6.8 | 4.7,4.9 |
| H-11 | Polystyrene Powder | 24.0,24.0,22.1 | 20.0,23.4 | 21.8,19.6,19.9 | 6.4,5.2 |
| M-4 | Polyester Shavings | 8.4,9.1 | 7.9,7.0 | 6.9,6.3 | 4.8,4.6 |
| M-5 | PTFE Shavings | 4.2,5.7 | 6.7,5.9,5.4 | 1.5,1.3 | 0.9,1.2 |

11a

Appendix C
Sorbent Product Sources

## Inorganic Products

| Code | | Manufacturers |
|------|------|------|
| I-1 | Calidria Oilbestos | Union Carbide Corp.<br>Chemicals & Plastics Div.<br>270 Park Ave.<br>New York, N. Y.  10017 |
| I-2 | Carbon Composite | Harshaw Chemical Co.<br>1945 East 97th St.<br>Cleveland, Ohio  44106 |
| I-3 | Cenospheres | Brooklyn Polytechnic Institute |
| I-4 | Ekoperl | Grefco Inc.<br>3435 W. Lomita Blvd.<br>Torrance, Cal.  90505 |
| I-5 | Mistron ZSC | Cyprus Mines Corp.<br>United Sierra Div,<br>Box 1201<br>Trenton, N. J.  08606 |
| I-6 | Spillbinder | W. R. Grace & Co.<br>Zonolite Const. Products Div.<br>Oiliminator Department<br>62 Whittemore Ave.<br>Cambridge, Mass.  02140 |
| I-7 | Controil | Pollution Control Prods. Corp.<br>P. O. Box 22191<br>University Station<br>San Juan, Puerto Rico  00931 |
| I-8 | Vak-Tek | BASF Wyandotte Corp.<br>Wyandotte, Mich.  48192 |

## Natural Organic Products

| Code | | Manufacturers |
|------|--|---------------|
| N-1 | Oilblotter | Anderson Cob Mills, Inc.<br>Box 119<br>Maumee, Ohio 43537 |
| N-2 | Sorbol, white | Innova, Inc.<br>444 Ravenna Blvd.<br>Seattle, Wash. 98115 |
| N-3 | Petroleum Absorber Fiber | Conwed Corp.<br>2200 Highcrest Rd.<br>St. Paul, Minn. 55113 |
| N-4 | Petroleum Absorber B-4 Pad | Conwed Corp.<br>as above |
| N-5 | Sorbol, brown | Innova, Inc.<br>as above |
| N-6 | Hay | generally available |
| N-7 | Peanut hulls | Curtis A. McDaniel<br>Lot 7, Lakeview Trailer Park<br>Smyrna, Ga. 30080 |
| N-8 | Pine bark | Sequoia Forest Prods. Co.<br>P. O. Box 305<br>Dinuba, Cal. 93618 |
| N-9 | Mulch | Conwed Corp.<br>as above |
| N-10 | Pulverized newsprint | Royce F. Blackmon<br>2502 Junius<br>San Angelo, Texas 76901 |
| N-11 | Redwood, shredded | American Modoc Inc.<br>R & D Office<br>The Towers, Suite 313<br>Campbell, Cal. 95008 |
| N-12 | Sawdust | Rollo J. Kidd<br>Consulting Chemist<br>4811 Green Rd.<br>Cleveland, Ohio 44128 |
| N-13 | Straw, wheat | generally available |
| N-14 | Treated Wheat Straw | W. Fletcher Cabat<br>Concord Rd.<br>Billerica, Mass. 01821 |
| N-15 | Wheat Middlings | Conwed Corp.<br>as above |
| N-16 | Shur Plug | Shur-Plug Co., Inc.<br>P. O. Box 852<br>Ada, Okla. 74820 |
| N-17 | Wood Chips | Ellis Seddon<br>Cincinnati Fruit<br>Hartford, Mich. |

## Polymeric Foam Products

| Code | | Manufacturers |
|------|--------------------------|----------------------------------------------------------------|
| F-1  | Soakitome                | Structural Concepts<br>15120 Keswick St.<br>Van Nuys, Cal.  91405 |
| F-2  | Scott Industrial Foam    | Scott Paper Co.<br>Foam Div.<br>1500 E. 2nd St.<br>Chester, Pa.  19013 |
| F-3  | Stepanpol                | Stepan Chemical Co.<br>Edens and Winnetka<br>Northfield, Ill.  60093 |
| F-4  | Capillardiamin           | U. F. Chemical Corp.<br>37-20 58th St.<br>Woodside, N. Y.  11377 |

## Polymeric Hydrocarbon Products

| Code | | Manufacturers |
|------|------|------|
| H-1 | Tyvek | E. I. Du Pont de Nemours & Co. Centre Road Bldg. Wilmington, Del. 19898 |
| H-2 | Polyethylene fiber matted sheet | 3M Co. Ind. Spec. Prods. Dept. 3M Center St. Paul, Minn. 55101 |
| H-3 | Polyethylene fiber loose, "Fluff" | 3M same as above |
| H-4 | Polyethylene powder | Research Triangle Inst. P. O. Box 12194 Research Triangle Park North Carolina 27709 |
| H-5 | Granulated Waste Polyethylene | Celanese Plastics Co. P. O. Box 1000 Deer Park, Texas 77536 |
| H-6 | Polypropylene fiber | Hercules, Inc. Mat'ls. Science Div. Wilmington, Del. 19899 |
| H-7 | Polypropylene split fiber | Phillips Scientific Corp. Bartlesville, Okla. 74004 |
| H-8 | Agglomoweb | Collins & Aikman Corp. Ca-Vel, N. C. 27512 |
| H-9 | Typar | E. I. Du Pont de Nemours & Co. see above |
| H-10 | Polypropylene powder | Hercules, Inc. see above |
| H-11 | Guzz | Zorbitronics, Inc. 1238 Nuala Concord, California 94520 |

## Miscellaneous

| Code | | Manufacturers |
|------|--|---------------|
| M-1 | Fiberperl | Grefco, Inc.<br>3435 W. Lomita Blvd.<br>Torrance, Calif.  90505 |
| M-2 | Sorbent C | Clean Water, Inc.<br>P. O. Box 1002<br>Toms River, N. J.  08753 |
| M-3 | DPC | International Minerals and<br>Chem. Corp.<br>Libertyville, Ill.  60048 |
| M-4. | Polyester shavings | Rham Associates<br>P. O. Box R-12<br>McKenney, Va.  23872 |
| M-5 | Teflon shavings (PTFE) | No specific source |
| M-6 | Cura | Westinghouse Electric Corp.<br>Beaulah Road<br>Pittsburgh, Pa.  15235 |
| M-7 | Sea Serpent | Johns - Manville<br>22 E. 40th St.<br>New York, N. Y.  10016 |
| M.8 | Strickite | Strickman Inds., Inc.<br>P. O. Box 140<br>Orangebury, N. Y.  10962 |
| M-9 | Coal-wood-polyethylene | J. R. Simplot Co.<br>P. O. Box 912<br>Pocatello, Idaho  83201 |

Appendix D
Photographs of Sorbents
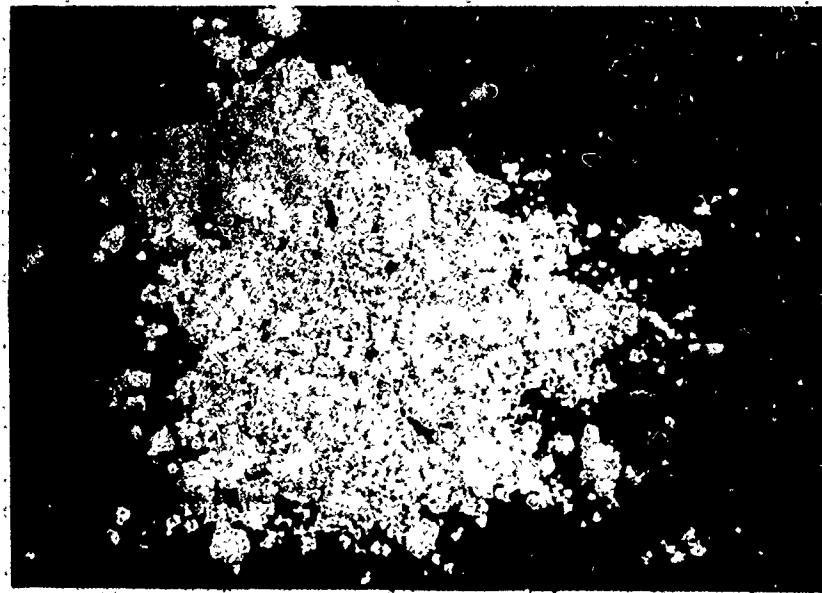
Figure 1-D
Asbestos (Chrysotile)
Code I-1



Figure 2-D
Carbon Composite
Code I-2
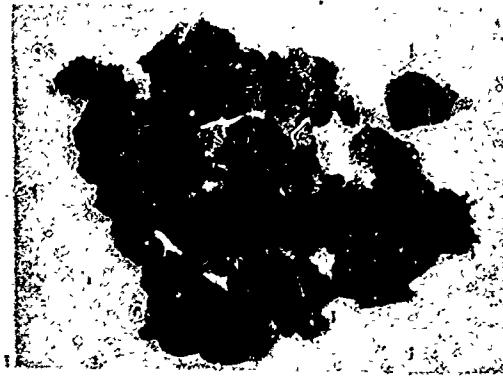


Figure 3-D
Fly Ash Component
Code I-3
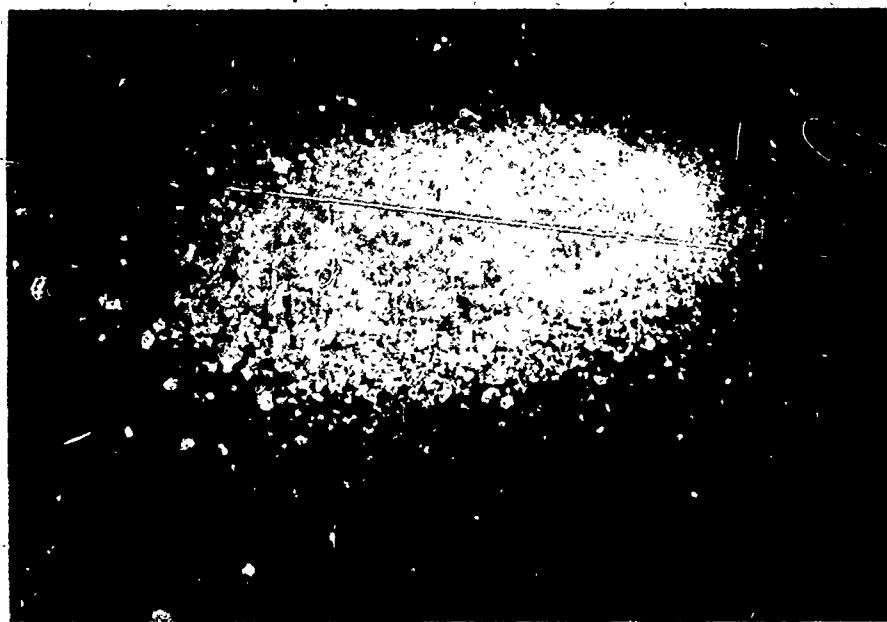
Figure 4-D,
Perlite
Code I-4



Figure 5-D
Talc
Code I-5



Figure 6-D
Vermiculite A
Code I-6
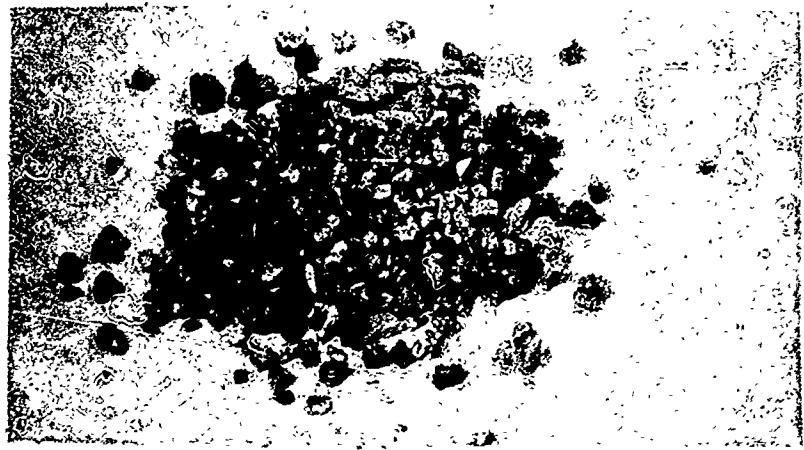
Figure 7-D
Vermiculite B
Code I-7



Figure 8-D
Volcanic Ash
Code I-8



Figure 9-D
Corn Cob (Ground)
Code N-1

D-3
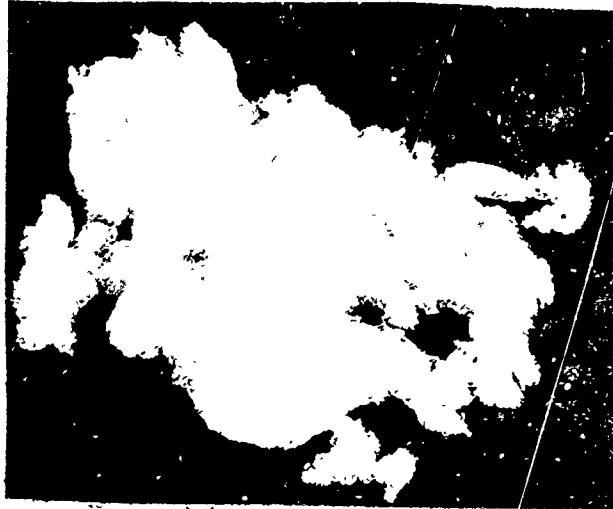
Figure 10-D
Cellulose, Bleached
Code N-2



Figure 11-D
Cellulose, Wood Fibers
Code N-3
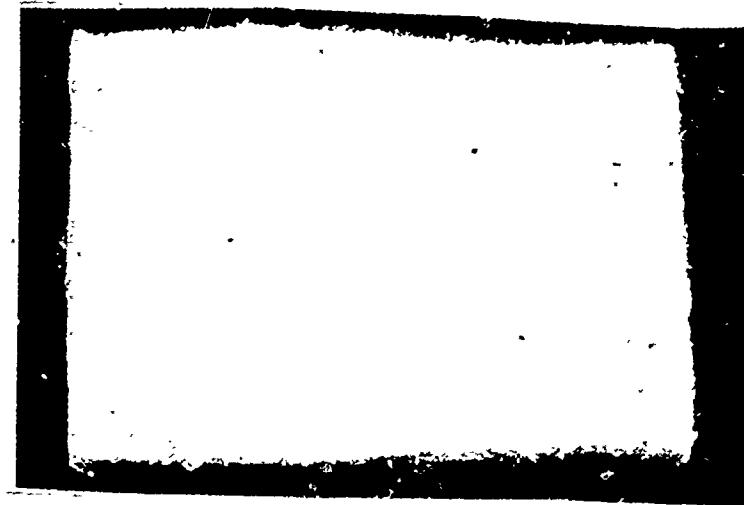


Figure 12-D
Cellulose, Wood Fiber Mat
Code N-4

Figure 13-D
Fiberboard, Recycled
Code N-5



Figure 14-D
Hay
Code N-6



Figure 15-D
Peanut Hulls, Ground
Code N-7
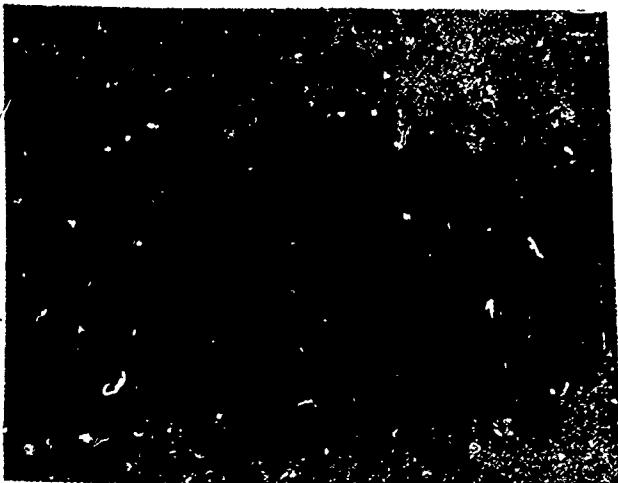
Figure 16-D
Pinebark, Ground
Code N-8
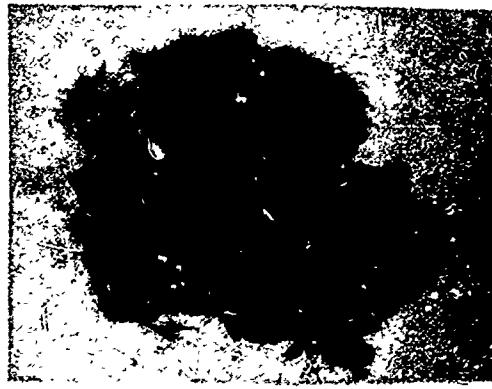
Figure 17-D
Mulch
Code N-9

Figure 18-D
Paper, Pulverized
Code N-10

Figure 19-D
Redwood, Shredded
Code N-11
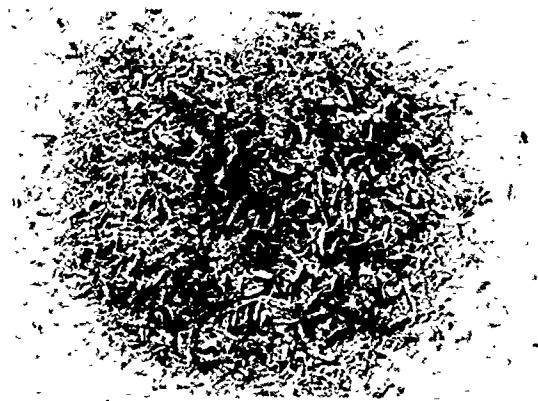


Figure 20-D
Sawdust
Code N-12
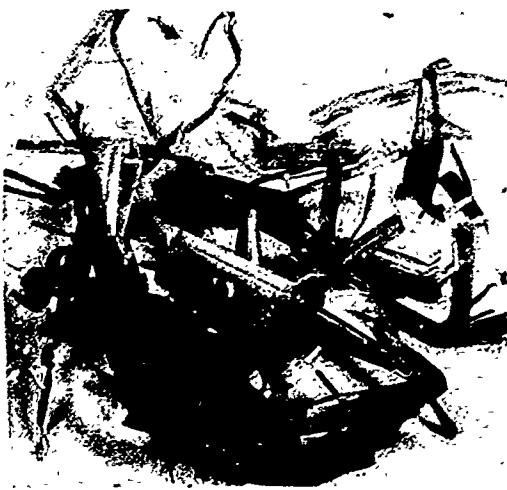


Figure 21-D
Straw, Wheat
Code N-13



Figure 22-D
Straw, Wheat (Treated)
Code N-14
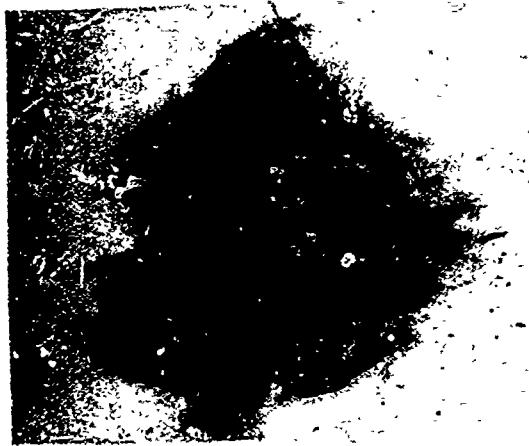
Figure 23-D
Wheat Middlings
Code N-15



Figure 24-D
Wood Chips A
Code N-16
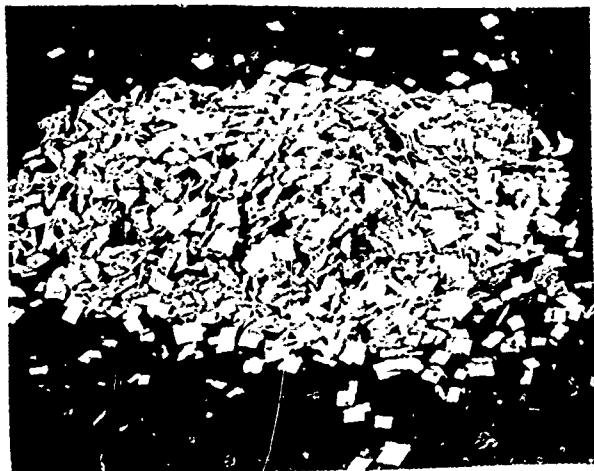


Figure 25-D
Wood Chips B
Code N-17
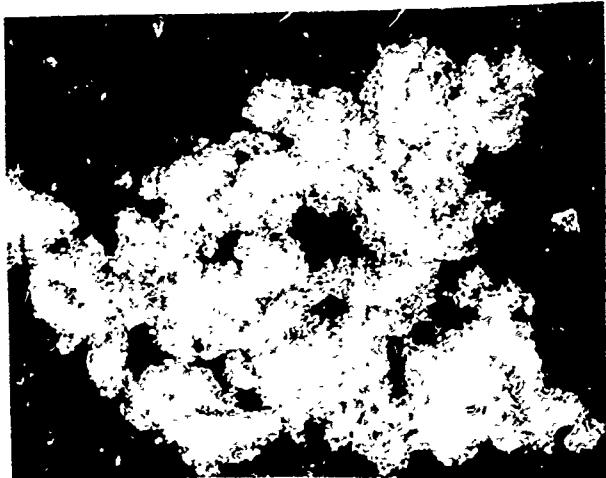


Figure 26-D
Polyurethane Foam,
Polyether, Shredded
Code F-1

Figure 27-D
Polyurethane Foam,
Polyester, Reticulated
Code F-2



Figure 28-D
Polyurethane Foam,
Polyether, 1/2 inch Cubes
Code F-3
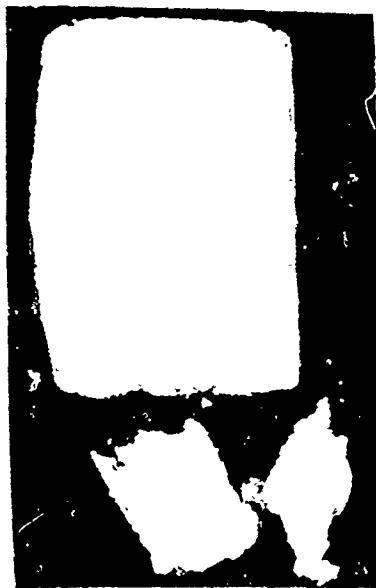


Figure 29-D
Urea Formaldehyde Foam
Code F-4



Figure 30-D
Polyethiene Fiber,
Continuous
Code H-1

Figure 31-D
Polyethylene Fiber, Matted Sheet
Code H-2
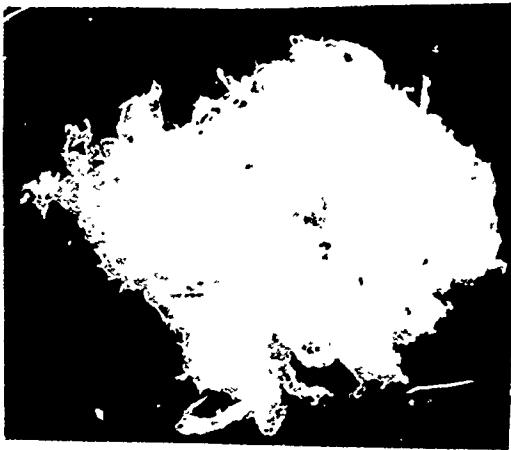


Figure 32-D
Polyethylene Fiber, Loose
Code H-3



Figure 33-D
Polyethylene Powder, Fine
Code H-4
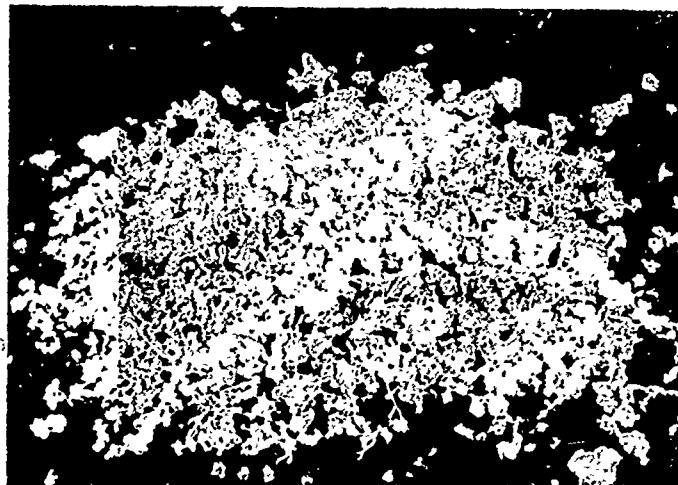
Code H-5

Figure 34-D
Polyethylene Granules, Waste
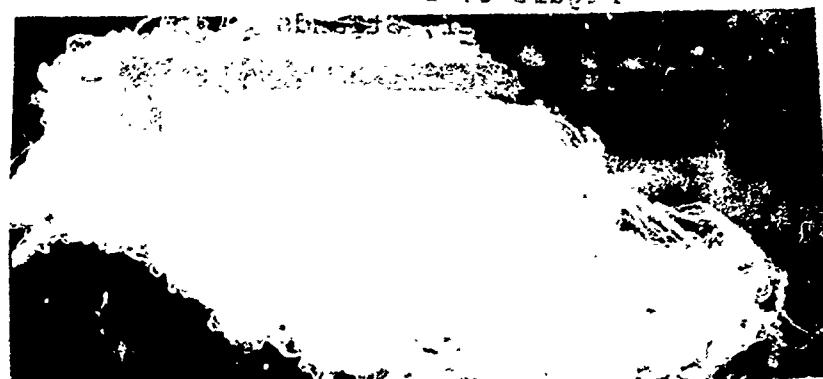


Code H-6

Figure 35-D
Polypropylene Fiber, Bulk A
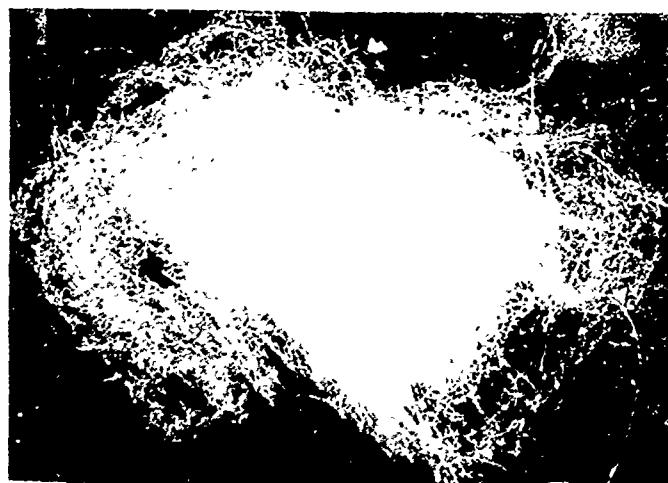


Code H-7

Figure 36-D
Polypropylene Fiber, Bulk B

D-11
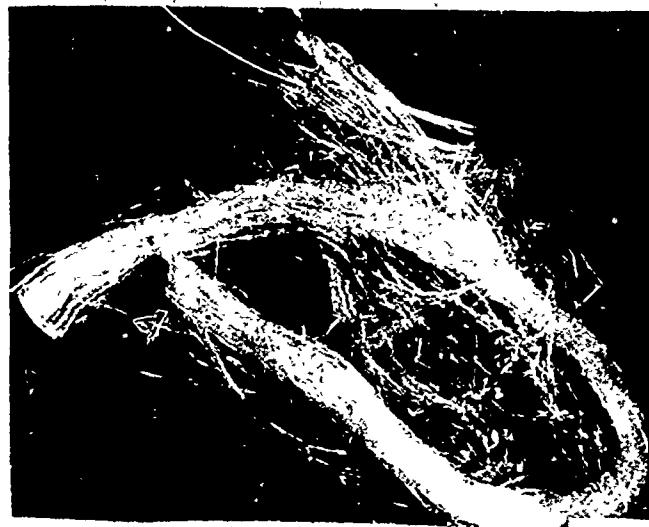
Code H-8

Figure 37-D
Polypropylene Fiber, Strands
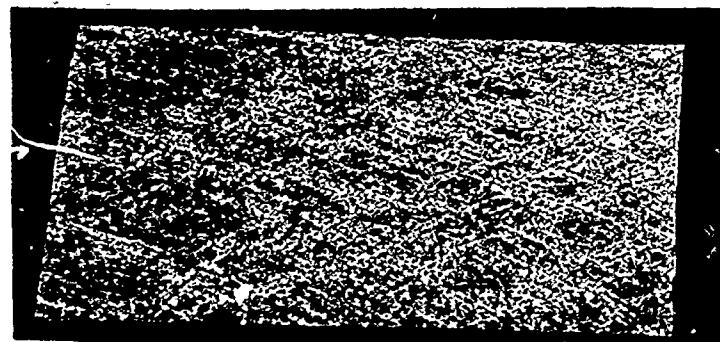


Code H-9

Figure 38-D
Polypropylene Fiber, Sheet
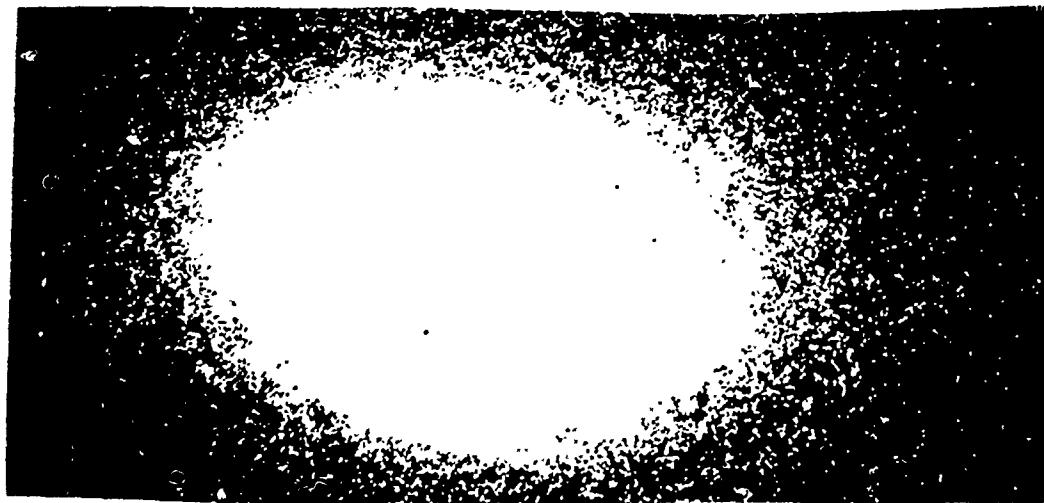


Code H-10

Figure 39-D
Polypropylene Powder
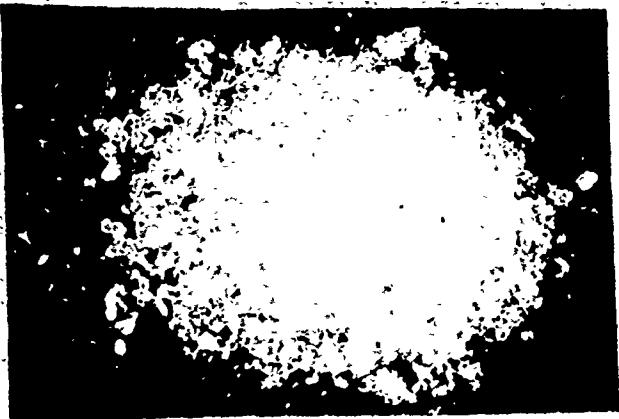
Figure 40-D
Polystyrene Powder

Code H-11



Figure 41-D
Cellulose Fiber-Perlite
Mixture A

Code M-1
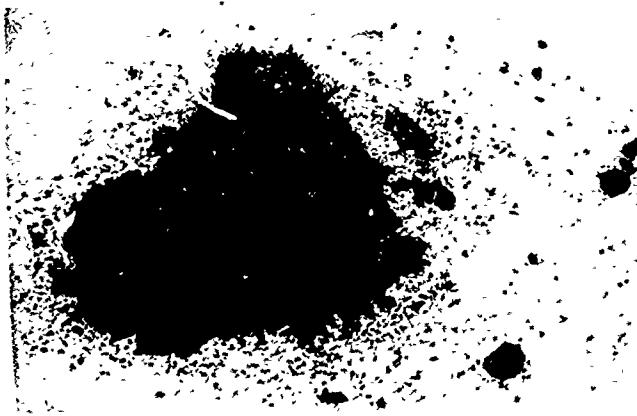


Figure 42-D
Cellulose Fiber-Perlite Mixture B

Code M-2



Figure 43-D
Fibrous Mixture

Code M-3

Figure 44-D
Polyester Plastic Shavings
Code M-4
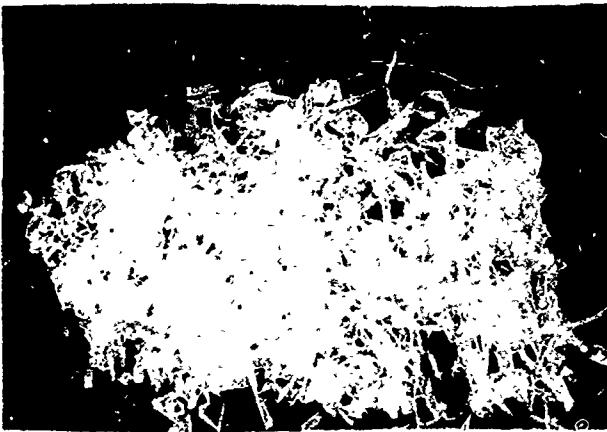


Figure 45-D
PTFE Shavings
Code M-5
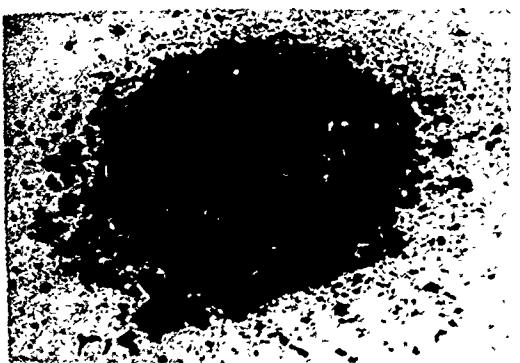


Figure 46-D
Refuse Compost
Code M-6



Figure 47-D
Synthetic Fiber Mixture
Code M-7
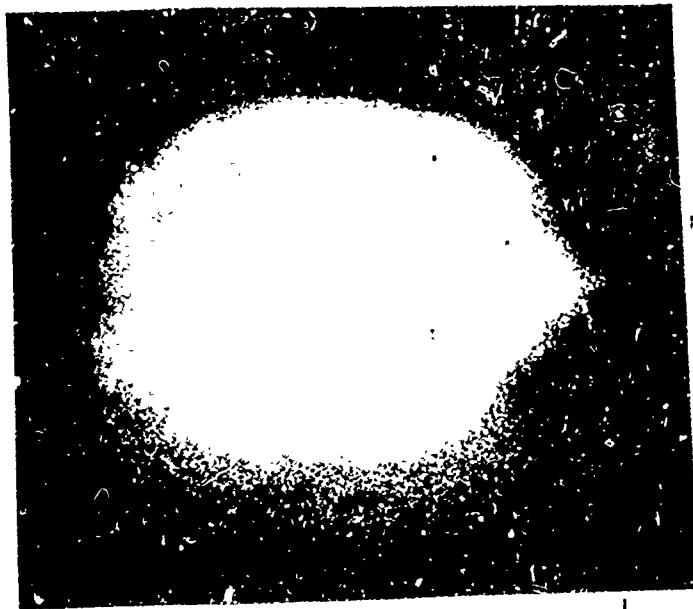
Figure 48-D
Synthetic Organic Powder
Code M-3



Figure 49-D
Wood-Coal-Polyethylene

Code M-9

Appendix E
Buoyancy Characteristics
and Photographs

## TABLE 1-E
## BUOYANCY CHARACTERISTICS
## INORGANIC PRODUCTS

| Code | Products | % Afloat After Shaking in Water for | | % Afloat After Shaking Oil-Soaked Sorbent in Water for 6 Hours | | | |
|------|----------|--------|------|-------------|----------------|----------------|-------------|
| | | 30 Min | 6 Hr | No. 2 Fuel | Light Crude | Heavy Crude | Bunker C |
| I-1 | Asbestos | 25 | 25 | 90 | 99 | 100 | 100 |
| I-2 | Carbon composite | 100 | 95* | 90 | 95 | 100 | 100 |
| I-3 | Fly ash component | 75 | 75 | - | 75 | 75 | 75 |
| I-4 | Perlite | 100 | 95* | 100 | 100 | 100 | 100 |
| I-5 | Talc | 10 | 0 | - | - | - | 100 |
| I-6 | Vermiculite A | 95 | 50* | 75 | 80 | 100 | 100 |
| I-7 | Vermiculite B | 95 | 50* | - | 100 | 100 | 100 |
| I-8 | Volcanic ash | 100 | 80* | 100 | 100 | 100 | 100 |

*fines sink

## TABLE 2-E
## BUOYANCY CHARACTERISTICS
## NATURAL ORGANIC PRODUCTS (VEGETABLE ORIGIN)

| Code | Products | % Afloat After Shaking in Water for | | % Afloat After Shaking Oil-Soaked Sorbent in Water for 6 Hours | | | |
|------|----------|--------|------|------------|----------------|----------------|-------------|
| | | 30 Min | 6 Hr | No. 2 Fuel | Light Crude | Heavy Crude | Bunker C |
| N-1 | Corn Cob, ground | 50 | 25 | 50 | 95 | 100 | 100 |
| N-2 | Cellulose, bleached | – | 10 | 80 | 90 | 100 | 100 |
| N-3 | Cellulose, wood fibers | 20 | 0 | – | 100 | 100 | 100 |
| N-4 | Cellulose, wood fiber mat | 10 | 0 | 20 | 25 | 100 | 100 |
| N-5 | Fiberboard, recycled | 95 | 80 | – | 100 | – | 100 |
| N-6 | Hay | 95 | 10 | – | 20 | 100 | 100 |
| N-7 | Peanut hulls, ground | 50 | 10 | 50 | 100 | 100 | 100 |
| N-8 | Pinebark, ground | 50 | 50 | 25 | 75 | 100 | 100 |
| N-9 | Mulch | 0 | 0 | 5 | 25 | 50 | 100 |
| N-10 | Paper, pulverized | 50 | 0 | 95 | 100 | 100 | 100 |
| N-11 | Redwood, shredded | 75 | 75 | – | 100 | 100 | 100 |
| N-12 | Sawdust | 95 | 50 | 100 | 100 | 100 | 100 |
| N-13 | Straw, wheat | 90 | 25 | 25 | 90 | 100 | 100 |
| N-14 | Straw, wheat, treated | 100 | 90 | – | 90 | 100 | 100 |
| N-16 | Wood chips A | 25 | 0 | – | 50 | 100 | 100 |
| N-17 | Wood chips B | 0 | 0 | – | 50 | 100 | 100 |
| N-15 | Wheat middlings | 0 | 0 | 10 | 50 | 100 | 100 |

TABLE 3-E
BUOYANCY CHARACTERISTICS
POLYMERIC FOAM PRODUCTS

| Code | Products | % Afloat After Shaking in Water for | | % Afloat After Shaking Oil-Soaked Sorbent in Water for 6 Hours | | | |
|------|----------|---------|------|------------|-------------|-------------|-----------|
| | | 30 Min | 6 Hr | No. 2 Fuel | Light Crude | Heavy Crude | Bunker C |
| | Polyurethane | | | | | | |
| F-1 | A. Polyether, shredded | 100 | 100 | 100 | 100 | 100 | 100 |
| F-2 | B. Polyester, reticulated | 100 | 100 | 100 | 100 | 100 | 100 |
| F-3 | C. Polyether, 1/2 in. cubes | 100 | 95* | 100 | 100 | 100 | 100 |
| F-4 | Urea formaldehyde | 100 | 80* | 100 | 100 | 100 | 100 |

*debris sinks

### TABLE 4-E
### BUOYANCY CHARACTERISTICS
### POLYMERIC HYDROCARBON PRODUCTS

| Code | Products | % Afloat After Shaking in Water for | | % Afloat After Shaking Oil-Soaked Sorbent in Water for 6 Hours | | | |
|------|----------|--------|------|---------------|--------------|--------------|-----------|
|      |          | 30 Min | 6 Hr | No. 2 Fuel | Light Crude | Heavy Crude | Bunker C |
|      | Polyethylene | | | | | | |
| H-1 | fiber, continuous | 100 | 100 | 100 | 100 | 100 | 100 |
| H-2 | fiber, sheet, matted | 100 | 100 | 100 | 100 | 100 | 100 |
| H-3 | fiber, loose | 100 | 100 | 100 | 100 | 100 | 100 |
| H-4 | powder, fine | 100 | 100 | 100 | 100 | 100 | 100 |
| H-5 | granules, waste | 100 | 100 | 100 | 100 | 100 | 100 |
|      | Polypropylene | | | | | | |
| H-6 | fiber, bulk A | 100 | 100 | 100 | 100 | 100 | 100 |
| H-7 | fiber, bulk B | 100 | 100* | 100 | 100 | 100 | 100 |
| H-8 | fiber, strands | 100 | 100* | 100 | 100 | 100 | 100 |
| H-9 | fiber, sheet | 100 | 100 | - | 100 | - | 100 |
| H-10 | powder | 100 | 100 | 100 | 100 | 100 | 100 |
| H-11 | Polystyrene powder | 100 | 100 | 100 | 100 | 100 | 100 |

*completely submerged below surface

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## TABLE 5-E
### BUOYANCY CHARACTERISTICS
### MISCELLANEOUS PRODUCTS

| Code | Products | % Afloat After Shaking in Water for | | % Afloat After Shaking Oil-Soaked Sorbent in Water for 6 Hours | | | |
|---|---|---|---|---|---|---|---|
| | | 30 Min | 6 Hr | No. 2 Fuel | Light Crude | Heavy Crude | Bunker C |
| M-6 | Refuse compost | 10 | 1 | – | 50 | 95 | 100 |
| M-1 | Cellulose fiber-perlite mixture A | 100 | 50 | 100 | 100 | 100 | 100 |
| M-2 | Cellulose fiber-perlite mixture B | 95 | 75 | 100 | 100 | 100 | 100 |
| M-3 | Fibrous mixture | 100 | 20 | – | 95 | 100 | 100 |
| M-7 | Synthetic fiber mixture | 95 | 90 | 100 | 100 | 100 | 100 |
| M-8 | Synthetic organic powder | 90 | 50 | 100 | 100 | 100 | 100 |
| M-4 | Polyester plastic shavings | 100 | 80 | 100 | 100 | 100 | 100 |
| M-5 | PTFE shavings | 100 | 100 | 100 | 100 | 100 | 100 |
| M-9 | Wood-coal-polyethylene | 100 | 70 | 95 | 100 | 100 | 100 |

Photographs of Sorbents After Shaking
in Sea Water for 6 Hours
Inorganic Products

Figure 1-E - Asbestos



Figure 2-E - Carbon Composite



Figure 3-E - Fly Ash
Component



Figure 4-E - Perlite

Figure 5-E - Talc



Figure 6-E - Vermiculite A



Figure 7-E - Vermiculite B



Figure 8-E - Volcanic Ash

Photographs of Sorbents After Shaking
in Sea Water for 6 Hours
Natural Organic Products

Figure 9-E - Corn Cob,
Ground



Figure 10-E - Bleached Cellulose



Figure 11-E - Wood Cellulose
Fiber



Figure 12-E - Wood Cellulose
Fiber Mat

Figure 13-E - Recycled
Fiberboard

Figure 14-E - Hay

Figure 15-E - Peanut Hulls,
Ground

Figure 16-E - Pulverized
Paper

Figure 17-E - Redwood
Shredded

Figure 18-E - Sawdust

Figure 19-E - Wheat Straw

Figure 20-E - Treated
Wheat Straw

Photographs of Sorbents After Shaking
in Sea Water for 6 Hours
Polymeric Foam Products

Figure 23-E - Poly-
urethane, Polyether,
1/2-Inch Cubes

Figure 24-E - Urea
Formaldehyde

Photographs of Sorbents After Shaking
in Sea Water for 6 Hours
Polymeric Hydrocarbon Products

Figure 25-E - Polyethylene
Fiber, Continuous



Figure 26-E - Polyethylene
Fiber, Sheet, Matted



Figure 27-E - Polyethylene
Fiber, Loose



Figure 28-E - Polyethylene
Powder, Fine

Figure 29-E - Polyethylene
Granules, Waste



Figure 30-E - Polypropylene
Fiber, Bulk A



Figure 31-E - Polypropylene
Fiber, Bulk B



Figure 32-E - Polypropylene
Fiber, Strands

Figure 33-E - Polypropylene
Powder



Figure 34-E - Polystyrene
Powder

Photographs of Sorbents After Shaking
in Sea Water for 6 Hours
Miscellaneous Products

Figure 35-E - Cellulose
Fiber-Perlite Mixture A



Figure 36-E - Cellulose
Fiber-Perlite Mixture B

Figure 37-E Fibrous
Mixture



Figure 38-E Polyester
Plastic Shavings



Figure 39-E - PTFE Shavings



Figure 40-E - Refuse Compost

Figure 41-E - Synthetic
Fiber Mixture



Figure 42-E - Synthetic
Organic Powder



Figure 43-E - Wood-Coal-
Polyethylene

Photographs of Oil-Soaked Sorbents After
Shaking in Sea Water for 6 Hours
Inorganic Products

Figure 44-E - Vermiculite A
and Light Crude Oil



Figure 45-E - Vermiculite B
and Bunker C Oil



Figure 46-E - Volcanic Ash
and No. 2 Fuel Oil



Figure 47-E - Volcanic Ash
and Light Crude Oil

Photographs of Oil-Soaked Sorbents After
Shaking in Sea Water for 6 Hours
Natural Organic Products

Figure 48-E - Cellulose
Wood Fiber and
Heavy Crude Oil



Figure 49-E - Ground Corn Cobs
and No. 2 Fuel Oil



Figure 50-E - Wheat Straw
and No. 2 Fuel Oil

Photographs of Oil-Soaked Sorbents After
Shaking in Sea Water for 6 Hours
Polymeric Foam Products
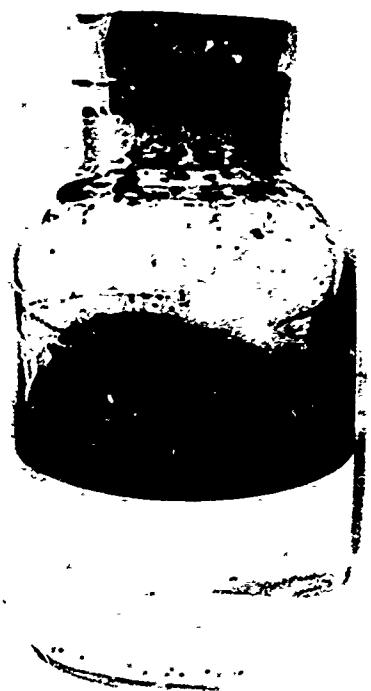
Figure 51-E - Polyurethane Foam
(Polyether, Shredded) and
Heavy Crude Oil



Figure 52-E - Polyurethane Foam
(Polyether, Shredded) and
Bunker C Oil



Figure 53-E - Polyurethane
(1/2 Inch Cubes) and
No. 2 Oil



Figure 54-E - Polyurethane Foam
(1/2 Inch Cubes) and
Light Crude Oil

Figure 55-E - Polyurethane Foam
(1/2 Inch Cubes) and
Heavy Crude Oil



Figure 56-E - Polyurethane Foam
(1/2 Inch Cubes) and
Bunker C Oil



Figure 57-E - Urea
Formaldehyde Foam and
Heavy Crude Oil



Figure 58-E Urea
Formaldehyde Foam and
Bunker C Oil

Photographs of Oil-Soaked Sorbents After
Shaking in Sea Water for 6 Hours
Polymeric Hydrocarbon Products

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Figure 59-E – Polyethylene Fiber
(Continuous) and
Heavy Crude Oil



Figure 60-E – Polyethylene Fiber
(Continuous) and
Bunker C Oil



Figure 61-C – Polyethylene Fiber
(Matted) and
Heavy Crude Oil



Figure 62-C – Polyethylene Fiber
(Loose) and
Heavy Crude Oil

Figure 63-E - Polyethylene
Fiber (Loose) and
Bunker C Oil

Figure 64-E - Polypropylene
Fiber (Strands) and
No. 2 Oil



Figure 65-E - Polypropylene
Fiber (Strands) and
Heavy Crude Oil

Photographs of Oil-Soaked Sorbents After
Shaking in Sea Water for 6 Hours
Miscellaneous Products

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Figure 66-C - Polyester Plastic
Shavings and Heavy Crude Oil



Figure 67-E - PTFE Plastic
Shavings and Light Crude Oil

Figure 68-E - PTFE Plastic
Shavings and Heavy Crude Oil



Figure 69-E - PTFE Plastic
Shavings and Bunker C Oil

Appendix F
Maximum Oil Sorption Capacity

## TABLE 1-F
### MAXIMUM OIL SORPTION CAPACITY
### INORGANIC PRODUCTS

| Code | Test Oils | Oil Sorption Capacity, g/g | | | |
|------|-----------|------------|------------|-------------|--------------|
| | | Bunker C | Heavy Crude | Light Crude | No. 2 Fuel |
| | Test Oil Viscosity at 77° F, cs | 2800 | 2600 | 7.8 | 3.1 |
| I-1 | Asbestos | 21.6 | 15.5 | 3.2 | 2.9 |
| I-2 | Carbon composite | 2.8 | 2.6 | 1.9 | 1.6 |
| I-3 | Fly ash component | 8.0 | * | * | * |
| I-4 | Perlite | 4.6 | 4.0 | 3.3 | 3.0 |
| I-5 | Talc | 8.6 | * | * | * |
| I-6 | Vermiculite A | 4.3 | 3.8 | 3.3 | 3.6 |
| I-7 | Vermiculite B | 4.2 | 4.2 | 1.7 | 1.2 |
| I-8 | Volcanic ash | 21.2 | 18.1 | 7.2 | 5.0 |

* results invalid, since most of sorbent passed through screen.

## TABLE 2-F
## MAXIMUM OIL SORPTION CAPACITY
## NATURAL ORGANIC PRODUCTS (VEGETABLE ORIGIN)

| Code | Test Oils | Oil Sorption Capacity, g/g | | | |
|------|-----------|---------|-------|-------|--------|
| | | Bunker C | Heavy Crude | Light Crude | No. 2 Fuel |
| | Test Oil Viscosity at 77° F, cs | 2800 | 2600 | 7.8 | 3.1 |
| N-1 | Corn cob, ground | 5.7 | 5.6 | 4.7 | 3.8 |
| N-2 | Cellulose, bleached | 5.9 | 6.8 | 4.4 | 5.0 |
| N-3 | Cellulose, wood fiber | 18.6 | 16.6 | 11.4 | 9.0 |
| N-4 | Cellulose, wood fiber mat | 16.2 | 13.8 | 9.6 | 12.7 |
| N-5 | Fiberboard, recycled | 21.0 | 18.2 | 9.8 | - |
| N-6 | Hay | 8.8 | 5.4 | 1.3 | 1.2 |
| N-9 | Mulch | 19.1 | 17.4 | 12.3 | 8.1 |
| N-7 | Peanut hulls, ground | 5.8 | 4.3 | 2.2 | 2.2 |
| N-8 | Pine bark, ground | 1.8 | 1.6 | 0.7 | 0.8 |
| N-10 | Paper, pulverized | 26.3 | 20.3 | 11.9 | 11.6 |
| N-11 | Redwood, shredded | 14.7 | 11.8 | 6.5 | 6.4 |
| N-12 | Sawdust | 4.0 | 3.7 | 3.6 | 2.8 |
| N-13 | Straw, wheat | 5.8 | 5.6 | 2.4 | 1.8 |
| N-14 | Straw, wheat, treated | 3.7 | 5.2 | 1.7 | 2.0 |
| N-15 | Wheat middlings | 19.8 | 16.8 | 12.7 | 7.0 |
| N-16 | Wood chips A | 2.8 | 3.2 | 2.2 | 1.9 |
| N-17 | Wood chips B | 3.0 | 2.7 | 2.0 | 1.0 |

## TABLE 3-F
## MAXIMUM OIL SORPTION CAPACITY
## POLYMERIC FOAM PRODUCTS

| Code | Test Oils | Oil Sorption Capacity, g/g | | | |
|------|-----------|---------|-------|-------|-------|
| | | Bunker C | Heavy Crude | Light Crude | No. 2 Fuel |
| | Test Oil Viscosity at 77° F, cs | 2800 | 2600 | 7.8 | 3.1 |
| | Polyurethane | | | | |
| F-1 | A. Polyether, shredded | 72.7 | 74.8 | 60.0 | 48.7 |
| | ... | | | | |
| F-2 | B. Polyester, reticulated | 30.3 | 24.5 | 30.6 | 27.5 |
| F-3 | C. Polyether, 1/2 inch cubes | 72.9 | 71.7 | 66.1 | 64.9 |
| F-4 | Urea formaldehyde | 72.7 | 52.4 | 50.3 | 47.8 |

## TABLE 4-F
### MAXIMUM OIL SORPTION CAPACITY
### POLYMERIC HYDROCARBON PRODUCTS

| Code | Test Oils | Oil Sorption Capacity, g/g | | | |
|------|-----------|-----------|-----------|-----------|-----------|
| | | Bunker C | Heavy Crude | Light Crude | No. 2 Fuel |
| | Test Oil Viscosity at 77° F, cs | 2800 | 2600 | 7.8 | 3.1 |
| | Polyethylene | | | | |
| H-1 | fiber, continuous | 46.0 | 36.7 | 45.4 | 36.2 |
| H-2 | fiber, sheet, matted | 18.6 | 17.6 | 11.9 | 10.6 |
| H-3 | fiber, loose | 37.0 | 27.8 | 19.7 | 16.1 |
| H-4 | powder, fine | 32.7 | 38.6 | 11.5 | 11.0 |
| H-5 | granules, waste | 7.4 | 6.4 | 3.9 | 3.7 |
| | Polypropylene | | | | |
| H-6 | fiber, bulk A | 44.0 | 38.6 | 29.8 | 28.4 |
| H-7 | fiber, bulk B | 66.0 | 64.8 | 38.0 | 40.5 |
| H-8 | fiber, strands | 21.7 | 18.1 | 6.9 | 4.8 |
| H-9 | fiber, sheet | 4.4 | 3.2 | 1.8 | 1.2 |
| H-10 | powder | 10.3 | 5.2 | 1.1 | 1.0 |
| H-11 | Polystyrene powder | 23.4 | 21.7 | 20.4 | 5.8 |

## TABLE 5-F
### MAXIMUM OIL SORPTION CAPACITY
### MISCELLANEOUS PRODUCTS

| Code | Test Oils | Oil Sorption Capacity, g/g | | | |
|------|-----------|----------|-------------|-------------|--------------|
| | | Bunker C | Heavy Crude | Light Crude | No. 2 Fuel |
| | Test Oil Viscosity at 77° F, cs | 2800 | 2600 | 7.8 | 3.1 |
| M-1 | Cellulose fiber-perlite mixture A | 9.5 | 10.8 | 9.1 | 6.2 |
| M-2 | Cellulose fiber-perlite mixture B | 12.1 | 13.7 | 9.8 | 6.7 |
| M-3 | Fibrous mixture | 11.4 | 6.1 | 4.5 | 4.7 |
| M-4 | Polyester plastic shavings | 8.8 | 7.4 | 6.6 | 4.7 |
| M-5 | PTFE shavings | 5.0 | 6.0 | 1.4 | 1.0 |
| M-6 | Refuse compost | 3.1 | 5.0 | 3.8 | 2.1 |
| M-7 | Synthetic fiber mixture | 16.9 | 16.0 | 9.8 | 8.7 |
| M-8 | Synthetic organic powder | 40.3 | 20.8 | 5.7 | 5.5 |
| M-9 | Wood-coal-polyethylene | 1.0 | 1.0 | 0.6 | 0.6 |

Appendix G
Water Sorption Capacity

## TABLE 1-G
## WATER SORPTION CAPACITY
## INORGANIC PRODUCTS

| Code | | Water Sorption Capacity, g/g after shaking for | |
|------|--|--------|--------|
| | | 30 Min | 6 Hr |
| I-1 | Asbestos | 2.4 | 3.1 |
| I-2 | Carbon composite | 0.4 | 0.5 |
| I-3 | Fly Ash component | * | * |
| I-4 | Perlite | 3.8 | 3.4 |
| I-5 | Talc | * | * |
| I-6 | Vermiculite A | 3.9 | 4.3 |
| I-7 | Vermiculite B | 4.1 | 4.4 |
| I-8 | Volcanic ash | 5.3 | 5.3 |

* results invalid, since most of sorbent passed through screen.

## TABLE 2-G
## WATER SORPTION CAPACITY
### NATURAL ORGANIC PRODUCTS (VEGETABLE ORIGIN)

| Code | | Water Sorption Capacity, g/g after shaking for | |
|------|--|--------|--------|
| | | 30 Min | 6 Hr |
| N-1 | Corn cob, ground | 6.4 | 6.3 |
| N-2 | Cellulose, bleached | 0.6 | 6.1 |
| N-3 | Cellulose, wood fiber | 12.7 | 12.8 |
| N-4 | Cellulose, wood fiber mat | 8.7 | 8.9 |
| N-5 | Fiberboard, recycled | 6.2 | 8.8 |
| N-6 | Hay | 6.3 | 5.0 |
| N-7 | Peanut hulls, ground | 2.7 | 6.5 |
| N-8 | Pine bark, ground | 1.1 | 0.7 |
| N-10 | Paper, pulverized | 15.2 | 15.2 |
| N-9 | Mulch | 11.2 | 13.9 |
| N-11 | Redwood, shredded | 7.6 | 7.6 |
| N-12 | Sawdust | 4.2 | 4.8 |
| N-13 | Straw, wheat | 4.9 | 5.3 |
| N-14 | Straw, wheat, treated | 2.3 | 3.4 |
| N-15 | Wheat middlings | 14.1 | 14.9 |
| N-16 | Wood chips A | 2.6 | 3.5 |
| N-17 | Wood chips B | 1.6 | 1.7 |

**TABLE 3-G**
**WATER SORPTION CAPACITY**
**POLYMERIC FOAM PRODUCTS**

| Code | | Water Sorption Capacity, g/g after shaking for | |
|---|---|---|---|
| | | 30 Min | 6 Hr |
| | Polyurethane | | |
| F-1 | A. Polyether, shredded | 40.9 | 33.5 |
| F-2 | B. Polyester, reticulated | 18.1 | 26.6 |
| F-3 | C. Polyether, 1/2 inch cubes | 36.5 | 41.6 |
| F-4 | Urea formaldehyde | 32.9 | 48.2 |

## TABLE 4-G
## WATER SORPTION CAPACITY
## POLYMERIC HYDROCARBON PRODUCTS

| Code | | Water Sorption Capacity, g/g after shaking for | |
|------|--|---------|--------|
| | | 30 Min | 6 Hr |
| | Polyethylene | | |
| H-1 | fiber, continuous | 7.0 | 11.5 |
| H-2 | fiber, sheet, matted | 1.8 | 5.6 |
| H-3 | fiber, loose | 2.5 | 5.4 |
| H-4 | powder, fine | 0.5 | 3.5 |
| H-5 | granules, waste | 1.1 | 0.9 |
| | Polypropylene | | |
| H-6 | fiber, bulk A | 1.8 | 3.4 |
| H-7 | fiber, bulk B | 30.7 | 28.0 |
| H-8 | fiber, strands | 2.9 | 4.7 |
| H-9 | fiber, sheet | 0.6 | 1.0 |
| H-10 | powder | 0.5 | 0.7 |
| H-11 | Polystyrene powder | 14.4 | 18.7 |

### TABLE 5-G
### WATER SORPTION CAPACITY
### MISCELLANEOUS PRODUCTS

| Code | | Water Sorption Capacity, g/g after shaking for | |
|------|---|---|---|
| | | 30 Min | 6 Hr |
| M-1 | Cellulose fiber-perlite mixture A | 5.1 | 5.7 |
| M-2 | Cellulose fiber-perlite mixture B | 4.5 | 6.0 |
| M-3 | Fibrous mixture | 4.7 | 4.2 |
| M-4 | Polyester plastic shavings | 6.1 | 6.6 |
| M-5 | PTFE shavings | 0.5 | 0.8 |
| M-6 | Refuse compost | 1.2 | 1 8 |
| M-7 | Synthetic fiber mixture | 9.6 | 9.8 |
| M-8 | Synthetic organic powder | 5.0 | 7.0 |
| M-9 | Wood-coal-polyethylene | 0.7 | 0.9 |

Appendix H
Oil/Water Sorption Capacity Ratio

## TABLE 1-H
### OIL/WATER SORPTION CAPACITY RATIOS
### INORGANIC PRODUCTS

| Code | Test Oils | Bunker C | Heavy Crude | Light Crude | No. 2 Fuel |
|------|-----------|----------|-------------|-------------|------------|
|      | Test Oil Viscosity at 77° F, cs | 2800 | 2600 | 7.8 | 3.1 |
| I-1  | Asbestos | 7.0 | 5.0 | 1.0 | 0.9 |
| I-2  | Carbon composite | 5.6 | 5.2 | 3.8 | 3.2 |
| I-4  | Perlite | 1.4 | 1.2 | 1.0 | 0.9 |
| I-6  | Vermiculite A | 1.0 | 0.9 | 0.8 | 0.8 |
| I-7  | Vermiculite B | 1.0 | 1.0 | 0.4 | 0.3 |
| I-8  | Volcanic ash | 4.0 | 3.4 | 1.4 | 0.9 |

## TABLE 2-H
### OIL/WATER SORPTION CAPACITY RATIOS
### NATURAL ORGANIC PRODUCTS (VEGETABLE ORIGIN)

| Code | Test Oils | Bunker C | Heavy Crude | Light Crude | No. 2 Fuel |
|------|-----------|----------|-------------|-------------|------------|
| | Test Oil Viscosity at 77° F, cs | 2800 | 2600 | 7.8 | 3.1 |
| N-1 | Corn cob, ground | 0.9 | 0.9 | 0.7 | 0.6 |
| N-2 | Cellulose, bleached | 1.0 | 1.1 | 0.7 | 0.8 |
| N-3 | Cellulose, wood fiber | 1.4 | 1.4 | 0.9 | 0.7 |
| N-4 | Cellulose, wood fiber mat | 1.8 | 1.6 | 1.1 | 1.4 |
| N-5 | Fiberboard, recycled | 2.4 | 2.1 | 1.1 | — |
| N-6 | Hay | 1.8 | 1.1 | 0.3 | 0.2 |
| N-7 | Peanut hulls, ground | 0.9 | 0.7 | 0.3 | 0.3 |
| N-8 | Pine bark, ground | 2.1 | 2.2 | 1.0 | 1.1 |
| N-9 | Mulch | 1.4 | 1.3 | 0.9 | 0.6 |
| N-10 | Paper, pulverized | 1.7 | 1.3 | 0.8 | 0.8 |
| N-11 | Redwood, shredded | 1.9 | 1.6 | 0.9 | 0.8 |
| N-12 | Sawdust | 0.8 | 0.8 | 0.8 | 0.6 |
| N-13 | Straw, wheat | 1.1 | 1.2 | 0.5 | 0.3 |
| N-14 | Straw, wheat, treated | 1.1 | 1.5 | 0.5 | 0.6 |
| N-15 | Wheat middlings | 1.3 | 1.1 | 0.9 | 0.5 |
| N-16 | Wood chips A | 0.8 | 0.9 | 0.6 | 0.5 |
| N-17 | Wood chips B | 1.8 | 1.6 | 1.2 | 0.6 |

TABLE 3-F
OIL/WATER SORPTION CAPACITY RATIOS
POLYMERIC FOAM PRODUCTS

| Code | Test Oils | Bunker C | Heavy Crude | Light Crude | No. 2 Fuel |
|---|---|---|---|---|---|
| | Test Oil Viscosity at 77° F, cs | 2800 | 2600 | 7.8 | 3.1 |
| | Polyurethane | | | | |
| F-1 | A. Polyether, shredded | 2.2 | 2.2 | 1.8 | 1.5 |
| F-2 | B. Polyester, reticulated | 1.1 | 0.9 | 1.2 | 1.0 |
| F-3 | C. Polyether, 1/2 inch cubes | 1.8 | 1.7 | 1.6 | 1.6 |
| F-4 | Urea formaldehyde | 1.5 | 1.1 | 1.0 | 1.0 |

## TABLE 4-H
### OIL/WATER SORPTION CAPACITY RATIOS
### POLYMERIC HYDROCARBON PRODUCTS

| Code | Test Oils | Bunker C | Heavy Crude | Light Crude | No. 2 Fuel |
|------|-----------|----------|-------------|-------------|------------|
|      | Test Oil Viscosity at 77° F, cs | 2800 | 2600 | 7.8 | 3.1 |
|      | Polyethylene |  |  |  |  |
| H-1  | fiber, continuous | 4.0 | 3.2 | 3.9 | 3.1 |
| H-2  | fiber, sheet, matted | 3.3 | 3.1 | 2.1 | 1.9 |
| H-3  | fiber, loose | 6.9 | 5.1 | 3.6 | 3.0 |
| H-4  | powder, fine | 9.3 | 11.0 | 3.3 | 3.1 |
| H-5  | granules, waste | 8.2 | 7.1 | 4.3 | 4.1 |
|      | Polypropylene |  |  |  |  |
| H-6  | fiber, bulk A | 12.9 | 11.4 | 8.8 | 8.4 |
| H-7  | fiber, bulk B | 2.4 | 2.3 | 1.4 | 1.4 |
| H-8  | fiber, strands | 4.6 | 3.9 | 1.5 | 1.0 |
| H-9  | fiber, sheet | 4.4 | 3.2 | 1.8 | 1.2 |
| H-10 | powder | 14.7 | 7.4 | 1.6 | 1.4 |
| H-11 | Polystyrene powder | 1.3 | 1.2 | 1.1 | 0.3 |

## TABLE 5-H
## OIL/WATER SORPTION CAPACITY RATIOS
## MISCELLANEOUS PRODUCTS

| Code | Test Oils | Bunker C | Heavy Crude | Light Crude | No. 2 Fuel |
|------|-----------|----------|-------------|-------------|------------|
| | Test Oil Viscosity at 77° F, cs | 2800 | 2600 | 7.8 | 3.1 |
| M-1 | Cellulose fiber-perlite mixture A | 1.7 | 1.9 | 1.6 | 1.1 |
| M-2 | Cellulose fiber-perlite mixture B | 2.0 | 2.3 | 1.6 | 1.1 |
| M-3 | Fibrous mixture | 2.7 | 1.5 | 1.1 | 1.1 |
| M-4 | Polyester plastic shavings | 1.3 | 1.1 | 1.0 | 0.7 |
| M-5 | PTFE shavings | 6.3 | 7.5 | 1.8 | 1.3 |
| M-6 | Refuse compost | 1.7 | 2.8 | 2.1 | 1.2 |
| M-7 | Synthetic fiber mixture | 1.7 | 1.6 | 1.0 | 0.9 |
| M-8 | Synthetic organic powder | 5.8 | 3.0 | 0.8 | 0.8 |
| M-9 | Wood-coal-polyethylene | 1.1 | 1.1 | 0.7 | 0.7 |

Appendix I
Oil Retention

## TABLE 1-I
## OIL RETENTION, %
## INORGANIC PRODUCTS

| Code | Test Oils | Bunker C | Heavy Crude | Light Crude | No. 2 Fuel |
|------|-----------|----------|-------------|-------------|------------|
| I-1 | Asbestos | 78 | 51 | 34 | 39 |
| I-2 | Carbon composite | 79 | 85 | 89 | 79 |
| I-4 | Perlite | 85 | 66 | 59 | 70 |
| I-5 | Talc | 85 | – | – | – |
| I-6 | Vermiculite A | 93 | 76 | 82 | 58 |
| I-7 | Vermiculite B | 82 | 84 | 67 | 66 |
| I-8 | Volcanic ash | 70 | 72 | 72 | 100 |

TABLE 2-I
OIL RETENTION, %
NATURAL ORGANIC PRODUCTS (VEGETABLE ORIGIN)

| Code | Test Oils | Bunker C | Heavy Crude | Light Crude | No. 2 Fuel |
|------|-----------|----------|-------------|-------------|------------|
| N-1 | Corn cob, ground | 88 | 88 | 69 | 27 |
| N-2 | Cellulose, bleached | 98 | 91 | 86 | 54 |
| N-3 | Cellulose, wood fiber | 92 | 70 | 55 | 55 |
| N-4 | Cellulose, wood fiber mat | 90 | 95 | 31 | 37 |
| N-5 | Fiberboard, recycled | 85 | 84 | 63 | - |
| N-6 | Hay | 100 | 100 | 77 | 50 |
| N-7 | Peanut hulls, ground | 58 | 85 | 70 | 27 |
| N-8 | Pine bark, ground | 6 | - | 14 | - |
| N-9 | Mulch | 63 | 50 | 28 | 28 |
| N-10 | Paper, pulverized | 80 | 88 | 48 | 41 |
| N-11 | Redwood, shredded | 78 | 50 | 43 | - |
| N-12 | Sawdust | 73 | 60 | 63 | 73 |
| N-13 | Straw, wheat | 98 | 92 | 67 | 39 |
| N-14 | Straw, wheat, treated | 92 | 100 | 65 | 50 |
| N-15 | Wheat middlings | 84 | - | 43 | - |
| N-16 | Wood chips A | 82 | 75 | 41 | 47 |
| N-17 | Wood chips B | 70 | 89 | 45 | 30 |

### TABLE 3-I
### OIL RETENTION, %
### POLYMERIC FOAM PRODUCTS

| Code | Test Oils | Bunker C | Heavy Crude | Light Crude | No. 2 Fuel |
|------|-----------|----------|-------------|-------------|------------|
|      | Polyurethane | | | | |
| F-1 | A. Polyether, shredded | 69 | 67 | 45 | 47 |
| F-2 | B. Polyester, reticulated | 87 | 93 | 74 | 77 |
| F-3 | C. Polyether, 1/2 inch cubes | 89 | 100 | 71 | 82 |
| F-4 | Urea formaldehyde | 97 | 73 | 55 | 43 |

## TABLE 4-I
### OIL RETENTION, %
### POLYMERIC HYDROCARBON PRODUCTS

| Code | Test Oils | Bunker C | Heavy Crude | Light Crude | No. 2 Fuel |
|------|-----------|----------|-------------|-------------|------------|
| | Polyethylene | | | | |
| H-1 | Fiber, continuous | 90 | 75 | 78 | 73 |
| H-2 | Fiber sheet, matted | 99 | 100 | 100 | 95 |
| H-3 | Fiber, loose | 65 | 100 | 82 | 67 |
| H-4 | Powder, fine | 80 | 66 | 75 | 78 |
| H-5 | Granules, waste | 76 | 84 | 64 | 76 |
| | Polypropylene | | | | |
| H-6 | Fiber, bulk A | 91 | 91 | 86 | 89 |
| H-7 | Fiber, bulk B | 74 | 83 | 75 | 36 |
| H-8 | Fiber, strands | 68 | 74 | 76 | 60 |
| H-9 | Fiber, sheet | 100 | 75 | 81 | 67 |
| H-10 | Powder | 100 | 63 | 84 | 29 |
| H-11 | Polystyrene powder | 81 | 77 | 53 | 29 |

I-4

## TABLE 5-I
## OIL RETENTION. %
## MISCELLANEOUS PRODUCTS

| Code | Test Oils | Bunker C | Heavy Crude | Light Crude | No. 2 Fuel |
|------|-----------|----------|-------------|-------------|------------|
| M-1 | Cellulose fiber-perlite mixture A | 81 | 63 | 71 | 65 |
| M-2 | Cellulose fiber-perlite mixture B | 100 | 69 | 56 | 82 |
| M-3 | Fibrous mixture | 65 | 82 | 54 | - |
| M-4 | Polyester plastic shavings | 65 | 56 | 67 | 61 |
| M-5 | PTFE shavings. | 80 | 84 | 73 | 45 |
| M-6 | Refuse Compost. | 87 | 76 | 16 | 38 |
| M-7 | Synthetic fiber mixture | 79 | 78 | 81 | 59 |
| M-8 | Synthetic organic powder | 92 | 63 | 66 | 58 |
| M-9 | Wood-coal-polyethylene | 100 | 100 | 83 | 100 |

Appendix J
Water/Oil Content Ratio After Shaking
Oil-Soaked Sorbent With Water

## TABLE 1-J
### WATER/OIL CONTENT RATIO AFTER SHAKING
### OIL-SOAKED SORBENTS WITH WATER
### INORGANIC PRODUCTS

| Code | Test Oils | Bunker C | Heavy Crude | Light Crude | No. 2 Fuel |
|------|-----------|----------|-------------|-------------|------------|
| I-1 | Asbestos | 0.6 | 0.2 | 0.1 | 0.1 |
| I-2 | Carbon composite | 0.4 | 0.2 | 0.1 | 0.05 |
| I-4 | Perlite | 0.4 | 0.2 | 0.2 | 0.2 |
| I-6 | Vermiculite A | 0.7 | 0.3 | 1.0 | 1.4 |
| I-7 | Vermiculite B | 0.7 | 0.2 | 0.6 | 0.4 |
| I-8 | Volcanic ash | 2.4 | 0.2 | 0.2 | 0.1 |

## TABLE 2-J
## WATER/OIL CONTENT RATIO AFTER SHAKING
## OIL-SOAKED SORBENT WITH WATER
## NATURAL ORGANIC PRODUCTS (VEGETABLE ORIGIN)

| Code | Test Oils | Bunker C | Heavy Crude | Light Crude | No. 2 Fuel |
|------|-----------|----------|-------------|-------------|------------|
| N-1 | Corn cob, ground | 0.6 | 0.3 | 0.8 | 0.5 |
| N-2 | Cellulose, bleached | 0.1 | 0.01 | 0.1 | 0.4 |
| N-3 | Cellulose, wood fiber | 0.6 | 0.1 | 0.1 | 0.3 |
| N-4 | Cellulose, wood fiber mat | 0.1 | 0.1 | 0.4 | 1.3 |
| N-5 | Fiberboard, recycled | 2.3 | 0.01 | 0.02 | - |
| N-6 | Hay | 1.1 | 0.9 | 2.6 | 2.0 |
| N-7 | Peanut hulls, ground | 0.8 | 0.3 | 0.3 | 1.0 |
| N-8 | Pine bark, ground | 0.4 | 0.4 | 0.7 | 0.8 |
| N-9 | Mulch | 0.6 | 0.7 | 0.5 | 1.3 |
| N-10 | Paper, pulverized | 1.1 | 0.05 | 0.9 | 1.2 |
| N-11 | Redwood, shredded | 1.0 | 0.3 | 0.6 | - |
| N-12 | Sawdust | 4.4 | 0.1 | 0.4 | 0.4 |
| N-13 | Straw, wheat | 0.9 | 0.6 | 1.5 | 2.1 |
| N-14 | Straw, wheat, treated | 1.9 | 0.1 | 1.5 | 1.0 |
| N-15 | Wheat middlings | 0.6 | - | 0.7 | - |
| N-16 | Wood chips A | 1.4 | 0.3 | 0.7 | 0.6 |
| N-17 | Wood chips B | 1.9 | 0.1 | 0.4 | 0.4 |

TABLE 3-J
WATER/OIL CONTENT RATIO AFTER SHAKING
OIL-SOAKED SORBENT WITH WATER
POLYMERIC FOAM PRODUCTS

| Code | Test Oils | Bunker C | Heavy Crude | Light Crude | No. 2 Fuel |
|------|-----------|----------|-------------|-------------|------------|
|      | Polyurethane |        |             |             |            |
| F-1  | A. Polyether, shredded | 1.3 | 0.3 | 0.2 | 0.1 |
| F-2  | B. Polyester, reticulated | 0.2 | 0.2 | 0.3 | 0.2 |
| F-3  | C. Polyether, 1/2 inch cubes | 1.1 | 0.2 | 0.2 | 0.01 |
| F-4  | Urea formaldehyde | 1.1 | 0.1 | 0.1 | 0.1 |

## TABLE 4-J
## WATER/OIL CONTENT RATIO AFTER SHAKING
## OIL-SOAKED SORBENT WITH WATER
## POLYMERIC HYDROCARBON PRODUCTS

| Code | Test Oils | Bunker C | Heavy Crude | Light Crude | No. 2 Fuel |
|------|-----------|----------|-------------|-------------|------------|
|      | Polyethylene |       |             |             |            |
| H-1  | Fiber, continuous | 0.05 | 0.01 | 0.1 | 0.02 |
| H-2  | Fiber, sheet, matted | 0.3 | 0.1 | 0.1 | 0.1 |
| H-3  | Fiber, loose | 0.6 | 0.04 | 0.2 | 0.1 |
| H-4  | Powder, fine | 2.5 | 0.1 | 0.1 | 0.04 |
| H-5  | Granules, waste | 1.0 | 0.1 | 0.3 | 0.2 |
|      | Polypropylene |      |             |             |            |
| H-6  | Fiber, bulk A | 0.1 | 0.01 | 0.03 | 0.1 |
| H-7  | Fiber, bulk B | 0.4 | 0.2 | 0.3 | 0.4 |
| H-8  | Fiber, strands | 0.8 | 0.6 | 0.3 | 0.4 |
| H-9  | Fiber, sheet | 1.8 | 0.2 | 0.2 | 0.2 |
| H-10 | Powder | 2.2 | 0.2 | 0.1 | 0.1 |
| H-11 | Polystyrene powder | 3.0 | 0.1 | 0.2 | 0.02 |

## TABLE 5-J
## WATER/OIL CONTENT RATIO AFTER SHAKING
## OIL-SOAKED SORBENT WITH WATER
## MISCELLANEOUS PRODUCTS

| Code | Test Oils | Bunker C | Heavy Crude | Light Crude | No. 2 Fuel |
|------|-----------|----------|-------------|-------------|------------|
| M-1 | Cellulose, fiber-perlite mixture A | 1.2 | 0.5 | 0.1 | 0.2 |
| M-2 | Cellulose, fiber-perlite mixture B | 0.6 | 0.6 | 0.04 | 0.1 |
| M-3 | Fibrous mixture | 0.6 | 0.3 | 0.03 | - |
| M-4 | Polyester plastic shavings | 3.0 | 0.05 | 0.2 | 0.3 |
| M-5 | PTFE shavings | 1.1; | 0.3 | 0.9 | 1.1 |
| M-6 | Refuse compost | 0.3 | 0.2 | 0.4 | 0.5 |
| M-7 | Synthetic fiber mixture | 0.3 | 0.1 | 0.1 | 0.4 |
| M-8 | Synthetic organic powder | 3.0 | 0.1 | 0.03 | 0.1 |
| M-9 | Wood-coal-polyethylene | 0.6 | 0.3 | 0.5 | 0.3 |

Appendix K
Oil Sorption Capacity Ratios
After/Before Shaking With Water

### TABLE 1-K
### OIL SORPTION CAPACITY RATIOS
### AFTER/BEFORE SHAKING WITH WATER
### INORGANIC PRODUCTS

| Code | Test Oils | Bunker C | Heavy Crude | Light Crude |
|------|-----------|----------|-------------|-------------|
| I-1 | Asbestos | 0.5 | – | 0.25 |
| I-2 | Carbon composite | 0.9 | 0.9 | 0.7 |
| I-4 | Perlite | 1.0 | – | 1.0 |
| I-6 | Vermiculite A | 0.6 | 0.5 | – |
| I-7 | Vermiculite B | 0.2 | 0.3 | 0.3 |
| I-8 | Volcanic ash | 0.7 | – | 0.5 |

## TABLE 2-K
### OIL SORPTION CAPACITY RATIOS,
### AFTER/BEFORE SHAKING WITH WATER
### NATURAL ORGANIC PRODUCTS (VEGETABLE ORIGIN)

| Code | Test Oils | Bunker C | Heavy Crude | Light Crude |
|------|-----------|----------|-------------|-------------|
| N-1 | Corn cob, ground | 1.0 | 0.6 | 0.3 |
| N-2 | Cellulose, bleached | - | 0.6 | - |
| N-3 | Cellulose, wood fiber | 1.0 | - | 0.2 |
| N-4 | Cellulose, wood fiber mat | 0.5 | - | - |
| N-5 | Fiberboard, recycled | 0.6 | 0.4 | - |
| N-6 | Hay | 0.9 | 0.6 | - |
| N-7 | Peanut hulls, ground | 0.8 | - | 0.3 |
| N-8 | Pine bark, ground | 0.3 | 0.6 | 0.3 |
| N-9 | Mulch | 0.4 | - | - |
| N-10 | Paper, pulverized | 0.2 | - | 0.03 |
| N-11 | Redwood, shredded | 0.4 | 0.7 | - |
| N-12 | Sawdust | 1.0 | 0.9 | 0.3 |
| N-13 | Straw, wheat | 1.0 | 0.9 | 0.8 |
| N-14 | Straw, wheat, treated | 1.0 | 0.5 | 0.8 |
| N-15 | Wheat middlings | 0.7 | - | - |
| N-16 | Wood chips A | 0.5 | 0.4 | 0.5 |
| N-17 | Wood chips B | 0.8 | 0.4 | - |

## TABLE 3-K
### OIL SORPTION CAPACITY RATIOS
### AFTER/BEFORE SHAKING WITH WATER
### POLYMERIC FOAM PRODUCTS

| Code | Test Oils | Bunker C | Heavy Crude | Light Crude |
|------|-----------|----------|-------------|-------------|
|  | Polyurethane |  |  |  |
| F-1 | A. Polyether, shredded | 0.6 | 0.6 | 0.5 |
| F-2 | B. Polyester, reticulated | 0.4 | 1.0 | 0.4 |
| F-3 | C. Polyether, 1/2 inch cubes | 0.3 | 0.5 | 0.4 |
| F-4 | Urea formaldehyde | 0.2 | 0.3 | – |

## TABLE 4-K
### OIL SORPTION CAPACITY RATIOS
### AFTER/BEFORE SHAKING WITH WATER
### POLYMERIC HYDROCARBON PRODUCTS

| Code | Test Oils | Bunker C | Light Crude |
|------|-----------|----------|-------------|
| | Polyethylene | | |
| H-1 | Fiber, continuous | 0.7 | 0.9 |
| H-2 | Fiber, sheet, matted | 1.0 | 1.0 |
| H-3 | Fiber, loose | 1.0 | 0.7 |
| H-4 | Powder, fine | 1.0 | 0.9 |
| H-5 | Granules, waste | 0.8 | 1.0 |
| | Polypropylene | | |
| H-6 | Fiber, bulk A | 0.8 | 0.9 |
| H-7 | Fiber, bulk B | 1.0 | 1.0 |
| H-8 | Fiber, strands | 0.9 | 0.7 |
| H-10 | Powder | 1.0 | 1.0 |
| H-11 | Polystyrene powder | 1.0 | – |

### TABLE 5-K
### OIL SORPTION CAPACITY RATIOS
### AFTER/BEFORE SHAKING WITH WATER
### MISCELLANEOUS PRODUCTS

| Code | Test Oils | Bunker C | Light Crude |
|------|-----------|----------|-------------|
| M-1 | Cellulose fiber-perlite mixture A | 1.0 | 1.0 |
| M-2 | Cellulose fiber-perlite mixture B | 1.0 | - |
| M-3 | Fibrous mixture | 0.4 | - |
| M-4 | Polyester plastic shavings | 1.0 | 0.6 |
| M-5 | PTFE shavings | 1.0 | 1.0 |
| M-6 | Refuse compost | - | 0.03 |
| M-7 | Synthetic fiber mixture | 0.8 | 0.9 |
| M-8 | Synthetic organic powder | 0.8 | - |
| M-9 | Wood-coal-polyethylene | 0.6 | 0.8 |